

**IN-SITU ENGINE EMISSIONS TESTING  
AND COMPARISON FOR A HIGH SPEED FERRY  
AND COMPETING LAND TRANSIT VEHICLE,  
PHASE I:  
TASK 7.0: Final Report**

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## EXECUTIVE SUMMARY

Phase I of the project for the In-Situ Engine Emissions Testing and Comparison for a High Speed Ferry and Competing Land Transit Vehicles comprises two aspects, divided into six tasks. The first aspect addresses the research and development of test methods and protocols for the comparison of emissions between the high-speed ferry and its competing land transit system, the diesel bus. The second aspect of Phase I is the review of current emissions reduction technologies that are applicable to the ferry.

The objective of the test program is to develop emissions rate factors for the same passenger-commute for the marine and land based vehicles of a pollutant expressed in grams/BHP-Hr and normalized for vehicle rider-ship (i.e. grams/passenger/day). The best available, laboratory-quality analyzers and test methods will be utilized in Phase II to measure emissions from the two sources to be tested. The same test methods, equipment and personnel will be used in both tests.

An extensive literature search was conducted that identified numerous protocols and standards for the measurement of emissions. Several references described emissions reduction technology and contained descriptions of testing methods either under consideration for use, or currently in use to demonstrate the effectiveness of a particular product. Industry experience and technical literature suggested that actual in-situ testing of an automobile will not be required for this study. A vast database of automobile emissions data is already available from the EPA. Therefore, the research focus is on the identification of test methods for the ferry and the diesel-powered bus.

There are two distinct issues relative to the development of test protocols for marine engines. The first is the need for a relatively simple and cost-effective test that can emerge as a standard for periodic emissions source testing. This low cost and easily implemented method would also serve the testing of various emissions reduction devices and alternative fuels. The second issue is the need for a detailed, laboratory-quality, field-adaptable protocol for the one-time testing of a diesel ferry in a particular service and a diesel bus in the same commuter service to create an absolute, scientifically defensible comparison. The technical literature offered ample information regarding cost-effective source test protocol. The literature also revealed a gap in the methods for conducting laboratory-quality field tests of passenger ferry engines and diesel passenger buses. Neither protocol exists for a satisfactory comparison.

This report concludes that well-established large-bore stationary diesel engine test methods are best suited for this analysis. This will be accomplished using extractive Fourier Transform Infrared Spectroscopy (FTIR) for testing of all targeted pollutants. The following pollutant species will be measured: acetaldehyde, acrolein, carbon 4+ straight-chain hydrocarbons, carbon dioxide, carbon monoxide, ethane, ethylene, formaldehyde and aldehyde compounds, methane, oxides of nitrogen (NO<sub>x</sub>), oxygen, particulate matter, sulfur dioxide, water vapor and any other FTIR-detected species. With FTIR, a single instrument will directly measure all targeted compounds and yield the highest quality data achievable utilizing any known test method. The FTIR analyzer will measure all targeted emissions simultaneously, in real-time, also enabling excellent measurement of engine transients.

The primary objective of obtaining precise real time in-situ data, comparing the exhaust emissions of competing auto, transit bus, and passenger ferry, remains unfinished. Until Phase II of the program element is completed, the actual emissions produced by competing transit modes, in particular buses and ferries, will remain undefined. The estimated time required for the in-situ testing portion of the Phase II effort is approximately 60 days. It is anticipated that another 60 days will be required for the proposed transit bus and ferry engine emissions test period to address all other administrative and contractual program requirements. This will permit some margin in the schedule in case of delays in obtaining test equipment or consumables, or to address any slippage due to the availability of the transit bus or ferry for testing. The total estimated cost for Phase II is \$204, 680.

Passenger ferries for harbor service employ high-speed marine diesel engines in the range of 150 to 3000 brake horsepower (BHP). Regarding emissions reduction technologies for ferries, it appears that the most effective approach for sulfur oxide (SOx) reductions is the use of high quality low sulfur (100 ppm) distillate fuel. Further sulfur reductions (to 15 ppm) are anticipated to occur in 2006. Public health initiatives today in some cases assign greater harm to NOx and particulate matter (PM) than to other exhaust gases, such as CO, CO<sub>2</sub> and unburned hydrocarbons (HC). For commuter-type passenger ferry application, using high-speed marine diesel engines, it currently appears that the most cost-effective method of partial NOx reduction is the use water-fuel emulsions. Additionally for NOx and PM control, exhaust gas recirculation (EGR) is often effective and minimally intrusive for an engine retrofit. Some new engines can be purchased with EGR built into the design, and some older engine designs can be modified to employ this technique. Used independently, or together with water-fuel emulsions, NOx emissions can be expected to drop dramatically, though not as significantly as the 90 percent reduction demonstrated by the technology of selective catalytic reduction (SCR). Although SCR is the single most effective NOx eliminator, the drawbacks include its volume in the exhaust system, and significant capital and life cycle costs.

Particulate filters, although effective at reducing PM, can raise the exhaust gas backpressure, in some cases enough to compromise engine efficiency and fuel economy. An oxidizing catalyst that fits into the exhaust system as a relatively inexpensive muffler replacement effectively reduces CO, HC and PM emissions, which can increase when NOx-control equipment is installed.

## 1.0 INTRODUCTION

United States ports are faced with severe air quality problems that threaten to prevent future growth. Major California ports are already operating at or above the limits of acceptable air quality, so that planned projects, such as harbor dredging for the Port of Oakland, new ferry transit operations, floating and shore-based power-generating stations, and the planned San Francisco Airport runway extension are all being held in abeyance pending solutions to mitigate the harmful emissions that these proposals, if approved, are projected to generate. A definite and growing need therefore exists to better assess the sources of air pollution and provide innovative, pragmatic solutions to reduce or eliminate harmful emissions from those sources, in particular from mobile sources, such as vehicles and vessels.

This project, conducted by Seaworthy Systems, Inc., will directly support CCDoTT goals by helping to obtain the facts about emissions -- where virtually no reliable, published data on modern marine diesel-powered ferry systems exist. The completed analysis could likely show that fast ferries either already are or can readily be made to be less polluting than automobiles and public buses in congested urban/suburban areas and thus support the establishment of a U.S. fast ferry industry. This project will present the required data to enable viable comparisons of land versus marine transit emissions and their relative contributions to regional air quality. Whatever the findings, the information obtained will permit planners and managers of both civilian and military operations to focus on meaningful solutions to the problem of total air quality. Phase I of this effort comprises a complete literature review, a definition of scope, approach and methodology for in-situ (field) vehicle emissions testing. Phase I also includes development of specific pollutant test protocols and specification of required test equipment, facilities and support systems.

Seaworthy Systems, Inc., with the assistance of its subcontractor, Advanced Engine Technologies Corporation (AETC), continues with the preparatory work for the performance of in-situ testing to compare the emissions from high-speed passenger ferries to competing land-based vehicles. This unique analysis will develop emissions rate factors a passenger-commute aboard marine and land-based vehicles for various pollutants, expressed in grams/BHP-Hr and normalized for vehicle ridership (i.e. grams/passenger/day).

The Phase I portion of this program has been segmented into the following discrete tasks.

|          |  |
|----------|--|
| Task 1.0 | Literature Search                        |
| Task 2.0 | Test Scope and Methodology Definition    |
| Task 3.0 | Test Protocol Development                |
| Task 4.0 | Test Equipment Specifications            |
| Task 5.0 | Phase II Schedule and Cost Estimate      |
| Task 6.0 | Emission Reduction Technology Evaluation |
| Task 7.0 | Final Report                             |



## **1.1 Objective**

The objective of this project is to review and analyze exhaust emissions from parallel passenger commuter vehicles — the urban bus and the passenger ferry. The project further includes research and recommendations for the engine emission-reduction technologies that are best suited for incorporation in diesel engines and propulsion systems in passenger ferry applications.

## **1.2 Program Background**

This program element comprises the definition, evaluation, and methods for the reduction of harmful emissions generated by three competing segments of the transportation sector — the largest single source of air pollution. Immediate and long-term program strategic objectives are to demonstrate how to optimize the air quality in ports by minimizing the regional sum of emissions generated by automobiles, transit buses, and passenger ferries. This optimization will foster progress for the agile port concept and in vessel and terminal design, improved public transit, increased port operational efficiency, and expanded cargo and passenger handling capabilities. Yet a lack of accurate data from mobile sources of emissions in ports damages programs that promise such benefits because of the public misperception that new development must always bring unacceptable hazards to health and the environment.

This report is part of the first portion of work (Phase I) to evaluate sources of the major mobile engine emissions in ports and to provide practical solutions to reduce exhaust emissions by diesel-powered ferry vessels. Phase I efforts an extensive technical literature search, a rational methodology for in-situ emissions testing, a list of required test instrumentation, test protocols, and estimates of cost and time to complete a projected Phase II program.

The Phase I research establishes that no credible emissions test results are available to conduct a fair comparison of diesel-powered transit buses and passenger ferry vessels. For various reasons, previous assessments of marine-propulsion emissions, in the absence of in-situ measurements, were consistently unreliable. Attempts to resolve emissions by source and quantity by a review of general literature or of vessel engine specifics (as published in Lloyd's Register) in combination with observed vessel traffic patterns have yielded inaccurate estimates. Consistently, such estimates are artificially high when compared to subsequent field tests. This overestimation has been noted in work by the southern California Port of Houston, and supported by tests conducted by the San Francisco Bay Area Water Transit Authority.

Phase I research also reveals deficiencies in the most recent efforts to gather emissions data from passenger ferries, by conducting field tests in Norfolk, Virginia and San Francisco, California in 2001 and 2002, respectively. These tests employed relatively inexpensive portable automotive test instrumentation. This equipment relied on bagging exhaust samples and transporting them to remote laboratories for analysis. Portable automotive test instrumentation and protocols are useful for comparing vector changes in quantities of emissions generated from a single engine type that undergoes various experimental modification, e.g. use of alternative fuels. However, such equipment is insufficient in both scope and accuracy for the comparison of one engine (as aboard a ferry) to another engine (as from a bus or auto). Tests designed to compare different transportation modes, with discrete operational profiles, atmospheric surroundings, and propulsion systems, require more sophisticated test instrumentation and more carefully planned test protocols. The utility-industry grade, state of the art, test instrumentation defined under Phase I for use in Phase II of this program element is of the highest scientific accuracy. When

combined with the engineering test protocols prepared under Phase I of this project, the final Phase II test results will be definitive, conclusive, and suitable for universal application.

## **2.0 LITERATURE SEARCH**

### **2.1 Objective**

The objective of this section is to review the available technical literature and identify laboratory-quality emission measurement methods and test protocols applicable for in-situ testing of exhaust emissions from marine diesel-cycle engines and diesel powered passenger buses. In addition, the goal is to identify methods for determination of emissions rate factors for automobiles serving the same commute. The results of the literature search will inform a test protocol for Phase II of this study.

### **2.2 Procedure**

The technical literature search utilized the following methods:

1. Review of in-house test reports and technical papers from AETC.
2. Search of the worldwide web via the Internet.
3. Discussions with regulatory agencies including the California Air Resources Board (CARB), the Environmental Protection Agency (EPA) and the South Coast Air Quality Management District (SCAQMD).
4. Review of governmental and industry supported technical societies including the U.S. Maritime Administration (MARAD), the American Bureau of Shipping (ABS), CIMAC (the European technical society for internal combustion engines) and the European Commission (EC).

The information obtained from all sources was reviewed and numerous candidate protocols were reviewed for applicability.

### **2.3 Search Results**

The search revealed numerous proposed protocols and test standards and found that a significant number of projects to develop protocols are currently underway. Several references for emissions reduction technologies described testing methods currently in use for product testing, or under consideration for use. A listing of reviewed sources, relevant to this program, follows.

#### **South Coast Air Quality Management District SCAQMD**

Rule 1631 Pilot Credit Generation Program for Marine Vessels

May 11, 2001

[www.aqmd.gov/rules/html/r1631.html](http://www.aqmd.gov/rules/html/r1631.html)

#### **BAE Systems**

Guide to Emission Control Options

March 2000

MS3026

Don Memers, Glenn Walters

**ISO/TC 70/SC 8**

TC 70: Internal Combustion Engines  
SC 8: Exhaust Emission Measurement  
Aug 10, 1994

**AG Environmental Products LLC**

9804 Pflumm RD  
Lenexa KS 66215

Product name: SoyGold

Description: Soydiesel used 2001-2002 on Blue and Gold Fleets in the San Francisco Bay area for emission reduction.

**SoyGold – Lubricity Study                      12/27/00**

Product literature on the effect of the soydiesel alternative on diesel engines.

**SoyGold – Material Safety Data Sheet; MSDS**

Case number 67784-80-9

**INNOVATION ‘Journal of the Association of Professional Engineers & Geoscientist of BC’**

Nov 2000 issue Page 12 “Continuous Water Injection”

Summary: Test results from ERMD (Emission Reduction & Means Division) 1998. Initial testing done by protocol on in-lab engines on a baseline to modification comparison.

**BioFuels DOE/GO-102001-1449**

September 2001

‘Biodiesel Explanation and Emission Results’

‘Biodiesel Fuel Properties’

**Dr. Anataoly D. Mezheritsky P.E.****“MA Turbo/Engine Design”**

‘Development of new low emission technology for diesel engines’ No date

Summary: Describes development of new low NOx emission technology tested on converted CAT 3406E/ Cummings NTC-350/ Wartsila 9R32D for EMRD. Lists test protocols used.

**J. Vollenweider, M. Geist and M. Schaub**

CIMAC 1995 Interlaken

‘Residual Fuels in Emission Controlled Diesel Engines’

Subject: Background development and operational results.

**Blue and Gold Fleet LP**

October 2001

‘Emission Reduction Demonstration Project’

Subject: Use of Biodiesel in Fleet. Test protocol and future testing.

**ABS Regulatory ‘Air Pollution Prevention’**

[www.eagle.org/regulatory/regupdate/mep39/air\\_pollution\\_prevention.htm](http://www.eagle.org/regulatory/regupdate/mep39/air_pollution_prevention.htm)

‘New annex to MARPOL’

‘Mandatory Code on NOx Reduction’

**BAE Systems- Guide to exhaust emission**

[www.cimac.com](http://www.cimac.com)

‘Control Options’

Andy Write ABS Europe LTD

**CIMAC Program for May 8, 2001**

[www.CIMAC.com](http://www.CIMAC.com)

‘Exhaust emissions- New Challenges in Emission Control’

A. Write ABS Europe LTD

**WTA Technical Advisory Committee**

“Clean Marine” Ad Hoc work group

November 16, 2001

‘Protocol development’

**Emission Standards: USA**

Heavy-Duty Truck and Bus Engines

Diesel Net

November 13, 2001

[www.dieselnet.com/standards/us/hd.html](http://www.dieselnet.com/standards/us/hd.html)

‘Emission Standards for New Engines’

‘California Urban Bus Standards’

‘Applicability and Test Cycles’

Summary: See Doc 2

**Emission Standards: USA**

Off-Road Engines

DieselNet

November 13, 2001

[www.dieselnet.com/standards/us/offroad.html](http://www.dieselnet.com/standards/us/offroad.html)

‘Harmonized with European Standards’

‘Marine Applications’

‘Emission Standards’

**Emission Standards: USA**

Marine Diesel Engines

DieselNet

November 13, 2001

[www.dieselnet.com/standards/us/marine.html](http://www.dieselnet.com/standards/us/marine.html)

‘Marine Diesel Engines’

‘MARPOL 73/78 Sept 27 1997’

‘MARPOL Annex VI Limits’

‘40CFRpart89’

‘Emission Standards cat1/ cat2’

‘Test Cycles- ISO8178 for cat 1’

‘Test Cycles- ISO8178 for cat 2’

Summary: See Doc 2

**Emission Standards: USA**

Urban Bus Retrofit Program

DieselNet

November 13, 2001

[www.dieselnet.com/standards/us/ubrr.html](http://www.dieselnet.com/standards/us/ubrr.html)

‘Urban Bus Retrofit Rebuild (UBRR) Program’

‘40CFRpart85subO’

**Emission Standards: USA**

Occupational Health Regulations

DieselNet

November 13, 2001

[www.dieselnet.com/standards/us/ohs.html](http://www.dieselnet.com/standards/us/ohs.html)

‘Regulatory Authorities’

‘Exposure Limits for Gasses’

‘Exposure Limits for Particulates’

**Emission Standards: EU**

Heavy-Duty Truck and Buses

DieselNet

November 13, 2001

[www.dieselnet.com/standards/eu/hd.html](http://www.dieselnet.com/standards/eu/hd.html)

‘Euro I-V Standards 1992’

‘Euro III Standard (Directive 1999/1996/EC)’

‘Emission Standards’

**Emission Standards: EU**

Emission Test Cycles

DieselNet

November 13, 2001

[www.dieselnet.com/standards/ecycles/ece\\_r49.html](http://www.dieselnet.com/standards/ecycles/ece_r49.html)

‘ECE R49 – 13 Mode Steady State Diesel Engine Test Cycle’

**Emission Standards: EU**

Emission Test Cycle; European Stationary Cycle (ESC)

DieselNet

November 13, 2001

[www.dieselnet.com/standards/cycles/ESC/.html](http://www.dieselnet.com/standards/cycles/ESC/.html)

‘ESC replaces R49 protocol’

**Emission Standards: EU**

European Load Response

DieselNet

November 13, 2001

[www.dieselnet.com/standards/cycles/elr.html](http://www.dieselnet.com/standards/cycles/elr.html)

‘Proposed smoke opacity measurement’

**Emission Standards: USA**

Heavy-Duty FTP Transient Cycle

DieselNet

November 13, 2001

[www.dieselnet.com/standards/cycles/ftp\\_trans.html](http://www.dieselnet.com/standards/cycles/ftp_trans.html)

‘On-Road Engine test (40CFR86.1333)’

‘New York/ Los Angeles Freeway Simulations’

**Emission Standards: USA**

Cars and Light-Duty Trucks

DieselNet

November 13, 2001

[www.dieselnet.com/standards/us/light.html](http://www.dieselnet.com/standards/us/light.html)

‘Emission Standards’

‘Federal Standards’

‘Tier I Standards’

‘Tier II Standards’

‘National LEV (Low Emission Vehicle) Program’

‘National LEV II (Low Emission Vehicle) Program’

‘California Standards’

‘Measured by Federal Test Procedures FTP-75’

**Emission Standards: USA**

Non-Road Vehicles

DieselNet

November 13, 2001

[www.dieselnet.com/standards/cycles/iso8178.html](http://www.dieselnet.com/standards/cycles/iso8178.html)

‘ISO 8178 Emission Test Cycles’

‘Non-Road Steady State Test Cycles’

‘Marine Test Cycles’

**Emission Standards: EU**

Light-Duty Vehicles

DieselNet

November 13, 2001

[www.dieselnet.com/standards/cycle/ece.eudc.html](http://www.dieselnet.com/standards/cycle/ece.eudc.html)

‘Chassis Dynamometer specifications for Light-Duty Vehicles’

**Emission Standards: Sweden**

Environmental Zones Program

DieselNet

November 13, 2001

[www.dieselnet.com/standards/se/zones.html](http://www.dieselnet.com/standards/se/zones.html)

‘‘City Zone Trucks and Buses July 1 1996’

‘Emission enforcement’

‘Emission Benefits’

**Emission Standards: EU**

Off-Road Diesel Engines

DieselNet

November 13, 2001

[www.dieselnet.com/standards/eu/offroad.html](http://www.dieselnet.com/standards/eu/offroad.html)

‘Off-Road Diesel Engine 97/68/EC’

**Emission Standards: SE**

Off-Road Engine Program

DieselNet

November 13, 2001

[www.dieselnet.com/standards/se/zones\\_off.html](http://www.dieselnet.com/standards/se/zones_off.html)

‘Emission requirements’

‘Equipment Certification’

**Emission Standards: SE**

Environmental Zones Program (Buses and Trucks)

DieselNet

November 13, 2001

[www.dieselnet.com/standards/se/zones.html](http://www.dieselnet.com/standards/se/zones.html)

‘Certification and Enforcement’

‘Chassis Dynamometer on “Braunschwig City Driving Cycle”’

**Emission Standards: EU**

Off-Road Diesel Engines

DieselNet

November 13, 2001

[www.dieselnet.com/standards/eu/offroad.html](http://www.dieselnet.com/standards/eu/offroad.html)

‘EU Emission Regulations for Off-road Diesels’



**Emission Standards: US**

Off-Road Engine Program

DieselNet

November 13, 2001

[www.dieselnet.com/standards/us/offroad.html](http://www.dieselnet.com/standards/us/offroad.html)

‘History Background’

‘Emission Standards’

‘Engine Useful Life’

‘Environmental Benefit and Cost’

Summary: EPA is currently working on a Test Protocol for Off-Road Diesel Engines.

**Emission Standards: Germany**

Occupational Health Regulations

DieselNet

November 13, 2001

[www.dieselnet.com/standards/de/ohs.html](http://www.dieselnet.com/standards/de/ohs.html)

‘Exposure Limits’

‘Diesel Engine Regulations’

‘Future Directions; Fine Particles’

**Emission Standards: Japan**

On-Road Vehicles and Engines

DieselNet

November 13, 2001

[www.dieselnet.com/standards/jp/onroad.html](http://www.dieselnet.com/standards/jp/onroad.html)

**Emission Standards: Japan**

Japanese 10-15 Mode

DieselNet

November 13, 2001

[www.dieselnet.com/standards/jp/jp\\_10-15mode.html](http://www.dieselnet.com/standards/jp/jp_10-15mode.html)

‘Light Duty test cycle’

**Emission Standards: Japan**

Japanese 13 Mode

DieselNet

November 13, 2001

[www.dieselnet.com/standards/jp/jp\\_13mode.html](http://www.dieselnet.com/standards/jp/jp_13mode.html)

‘Heavy-Duty Engine Test Cycle’

**EPA - Office of Transportation and Air Quality**

Volunteer Diesel Retrofit Program

[www.epa.gov/otaq/retrofit/retrotesting.htm](http://www.epa.gov/otaq/retrofit/retrotesting.htm)

Air Pollution Control Technology Verification Center

October 2, 2001

Draft Generic verification protocol for retrofit catalyst, particulate filter and engine modification control technologies for highway and non-road use diesel engines.

**Fairplay Solutions**

October 2001

Issue No 61

Page 8 “Dual Fuel Marine Engines”

**MARAD****Emissions Monitoring Protocols for Commercial Ships**

James J. Corbett P.E. PhD

Allen Robinson, PhD.

Alex Farrell, PhD.

[www.marad.dot.gov/MTS\\_RD/topics.html](http://www.marad.dot.gov/MTS_RD/topics.html)

**EPA****Test/QA procedures for verification of portable NO/NO<sub>2</sub> emission analyzers**

December 4, 1998

[www.epa.gov/etv/07/prot\\_no2.pdf](http://www.epa.gov/etv/07/prot_no2.pdf)

**MARPOL 73/78 Annex VI- Technical Code, International Maritime Organization.  
MP/CONF 3/35, 22 Oct 1997**

**MARPOL 73/78 Annex VI- International Maritime Organization, MP/CONF 3/34, 28 Oct 1997**

**R. Herrmann and G. Grosshans, “Exhaust Emissions of Ship Propulsion Engines” ASME  
Oct 1994**

**Research Project 396: Exhaust Gas Monitoring: Evaluation of Exhaust Gas Monitoring  
Equipment for Shipboard Use, Marine Information Note MIN 41 (M+F) Jan 1999**

**EPA**

EMC- CFR Promulgated Test Method

<http://www.epa.gov/ttn/emc/promgate.html>

**2.4 Discussion**

In consultation with AETC, and supported by industry experience and the results of this literature survey, we conclude that actual in-situ testing of an automobile will not be required for this study. This is due to the vast database of emissions data available from the EPA and other sources for automobile pollutant generation rates. Therefore, this review focused on the

identification of applicable test methods for the ferry, which could also apply to the test of the diesel-powered bus.

There are two distinct issues relative to the development of test protocols of marine engines. The first is the development of a relatively simple and cost-effective test that can be established as a broad-based standard for periodic emissions source testing. This low cost and easily implemented method would also apply to comparative testing of various emissions reduction devices and/or alternative fuels. The development and evaluation of such methods is currently underway by numerous groups as noted in the references.

The second issue, imperative to this study, is the generation of a detailed, laboratory-quality protocol applicable to the one-time testing of a diesel ferry in a particular service and a diesel bus in the same commuter service for the purpose of obtaining absolute, scientifically defensible data. The technical literature overwhelmingly offers information on the former, cost-effective source test protocol, while clearly demonstrating that results and/or the test methods utilized for conducting a laboratory quality field test of a marine ferry engine or diesel passenger bus are non-existent.

Therefore, we will move toward adapting well-established test methods for large-bore stationary diesel engines to the demands of this analysis. Based on a review of recent test work and emissions test protocol development performed by AETC for the New York State Department of Environmental Conservation and upon discussions with various agencies, this will primarily consist of the utilization of the extractive Fourier Transform Infrared Spectroscopy (FTIR) method for testing of all targeted pollutants.

Utilizing FTIR (EPA Method 320) a single instrument will directly measure all targeted compounds and will provide the highest quality data currently achievable utilizing any known test method. In addition, since the FTIR analyzer will measure all targeted compounds real-time, and the measurement of all compounds will occur simultaneously, excellent measurement of engine transients will be possible. We propose utilizing FTIR to measure the following compounds:

The following chemical species will be quantified:

- Acetaldehyde;
- Acrolein;
- Carbon4+ straight-chain hydrocarbons (aliphatic HCs, C<sub>4</sub> and larger);
- Carbon dioxide (CO<sub>2</sub>);
- Carbon monoxide (CO);
- Ethane;
- Ethylene;
- Formaldehyde and aldehyde compounds;
- Methane;
- Oxides of Nitrogen (NO<sub>x</sub>) (using NO + NO<sub>2</sub> on the FTIR);
- Oxygen (utilizing a paramagnetic analyzer);
- Particulate matter (utilizing EPA Method 5)

- Sulfur dioxide (SO<sub>2</sub>);
- Water vapor (H<sub>2</sub>O); and
- Any other FTIR-detected species.

The capability of the FTIR instrument to measure VOC's, methane and formaldehyde compounds in real-time with unsurpassed accuracy offers tremendous advantages over other indirect methods which would require the acquisition of an exhaust gas sample that is then sent (off-site) for laboratory analysis, typically utilizing "wet chemistry" methods.

As noted above, EPA Method 5 will be used for the measurement of particulate matter. EPA Method 5 is a mass-based particulate method, well established and universally accepted for stationary sources. The identical test equipment will be utilized for the in-situ test of the marine engines on the ferry as well as for measurement of the bus emissions while the bus is operated on a chassis dynamometer.

During the testing utilizing FTIR, we may recommend performing simultaneous testing with an inexpensive portable-type analyzer for the purposes of qualifying the portable instrument. Once qualified, the portable unit could be used for later portions of this analysis, which will evaluate various candidate emissions-reduction devices and/or alternative fuels.

### 3.0 TEST SCOPE AND METHODOLOGY DEFINITION

#### 3.1 Objective

The objective of this section is to define in broad terms the scope and methodology to conduct transit bus and passenger ferry emissions testing and to capture required engine load and performance data.

#### 3.2 Test Scope and Methodology

##### 3.2.1 Engine Exhaust Emissions Measurements

The imperative requirement of this research is the generation of a detailed, laboratory-quality protocol applicable to the one-time testing of a diesel engine powered ferry in a particular service and a diesel engine powered bus in the same commuter service for the purpose of obtaining absolute, scientifically defensible emissions data. Therefore, we will adapt well-established diesel engine test methods for use in this analysis. Utilizing Fourier Transform Infrared Spectroscopy Analysis, FTIR (EPA Method 320), a single instrument will directly measure all targeted compounds and will provide the highest quality data currently achievable utilizing any known test method. Moreover, since the FTIR analyzer will measure all targeted compounds in real-time, and the measurement of all compounds will occur simultaneously, excellent measurement of engine transients will be possible.

The following chemical species will be quantified:

- Acetaldehyde;
- Acrolein;
- Carbon4+ straight-chain hydrocarbons (aliphatic HCs, C<sub>4</sub> and larger);
- Carbon dioxide (CO<sub>2</sub>);
- Carbon monoxide (CO);
- Ethane;
- Ethylene;
- Formaldehyde and aldehyde compounds;
- Methane;
- Oxides of Nitrogen (NO<sub>x</sub>) (using NO + NO<sub>2</sub> on the FTIR);
- Oxygen (utilizing a paramagnetic analyzer);
- Particulate matter (utilizing EPA Method 5);
- Sulfur dioxide (SO<sub>2</sub>);
- Water vapor (H<sub>2</sub>O); and
- Any other FTIR-detected species.

To meet the objectives of this test program, it is essential to accurately capture engine power and speed (load) profiles for both the bus and the ferry. For the passenger ferry, this engine load data will be captured simultaneously with the exhaust emissions data. Regarding the transit bus, this data will be obtained in two-stages: (1) on-board testing to determine average daily engine load profile and passenger ridership profile and (2) chassis dynamometer testing with the engine load profile programmed into the dynamometer. A description of the engine parameters to be measured and the respective measurement methods follows.

### 3.2.2 Transit Bus Engine Performance Data Collection On-Board

Based on review of the bus routing and routine, the test team will ride a representative bus for not less than three (3) days. During this time, in addition to recording the number of passengers, a log will be created noting times and activities of the bus.

In addition, a portable PC based data acquisition system (DAQ) will be used to continuously monitor the minimum parameters listed in Table 3.1. These parameters will then be used for programming the chassis dynamometer for the emissions test work.

**Table 3.1**  
**Measured Parameters of the Transit Bus Test**

| <b>Parameter</b>  | <b>Measurement Method</b>      | <b>Purpose</b>  |
|---|--------------------------------|---|
| Fuel Flow   | Engine control module          | Input to emissions calculations.                      |
| Air manifold temperature  | “ “                            | To confirm engine operating condition on dynamometer. |
| Air manifold pressure   | “ “                            | “ “   |
| Jacket water temperature  | “ “                            | “ “   |
| Engine speed  | “ “                            | “ “   |
| Vehicle speed   | “ “                            | “ “   |
| Throttle position   | Linear displacement transducer | “ “   |
| Ambient temperature   | Thermometer                    | Input to emissions calculations.                      |
| Misc. engine operating data available from engine control module. |                                | Engine performance monitoring.                        |

As shown in Table 3.1, the majority of the data will be acquired through a serial-port (or similar) connection to the engine electronic control unit. Data not available from this source will be acquired from temporary, test-quality instrumentation, connected as analogue voltage inputs to the data acquisition computer.

Following the acquisition of the foregoing data, the test team will develop a time versus engine load and speed profile, relating the various engine operating conditions and the durations at which the engine operates at each load condition. In addition, the details of transients (i.e. acceleration /deceleration), observed during the onboard testing will be recorded.

#### Dynamometer Testing

Once the load profile is completely established, a test matrix will be generated for operation of the same bus on a chassis dynamometer. While field conditions are duplicated on the dynamometer, the engine performance data outlined in Table 3.1 will be captured in addition to, and simultaneously with, the emissions species outlined in Section 3.1 in real time. The data will be utilized to develop an accurate, scientifically defensible profile of emissions data for a fleet of buses.

#### Data Reduction.

For each of the steady-state conditions, not less than three (3) 30-minute test runs will be conducted on the dynamometer. For each of the transient conditions, each of the transient events will be tested not less than three (3) times. The three data sets of each type will be checked real-time to ensure that the data repeatability satisfies the criterion established in the test protocol. Tests yielding data unable to meet the repeatability standard as defined in the test protocol will be done again.

For the steady-state runs, the total mass emissions rates will be generated by multiplying the daily duration (hours) at the specific load condition by the emissions mass flow rates measured on the dynamometer (grams/hour). Similarly, for the transient data, the total mass of pollutants emitted during each transient (grams) will be multiplied by the number of transients of each type occurring each average day.

The total mass of the steady state and transient runs will then be summed to determine a total daily average mass emissions rate.

#### **3.2.3 Passenger Ferry Engine Performance Data Collection**

Engine operating data will be recorded simultaneously with emissions data, while aboard the vessel as it performs its usual schedule. Testing will consist of not less than three (3) days, as equal to the testing of the transit bus.

In addition to the emissions test equipment, the portable DAQ, supplemented by manual data entry, will be used to continuously monitor the minimum parameters listed in Table 3.2. These measured parameters include engine combustion airflow, exhaust flow, fuel consumption, power output, etc., as required to develop a complete description of the engine's operational condition for developing mass emissions rates in transient and steady state periods.

**Table 3.2**  
**Measured Parameters of the Passenger Ferry Test**

| <b>Parameter</b>            | <b>Measurement Method</b>             | <b>Purpose</b>  |
|-----------------------------|---------------------------------------|---|
| Fuel Flow (supply & return) | Test Meters connected to DAQ*         | Input to emissions calculations.  |
| Air manifold temperature    | RTD Connected to DAQ                  | Engine performance monitoring.  |
| Air manifold pressure       | Pressure transducer connected to DAQ. | Engine performance monitoring and to support emission rates calculations. |
| Jacket water temperature    | RTD Connected to DAQ                  | Engine performance monitoring.  |
| Shaft speed                 | From shaft torque meter               | Brake HP calculation.   |
| Shaft Torque                | From shaft torque meter.              | Brake HP calculation.   |
| Throttle position           | Linear displacement transducer        | Engine performance monitoring.  |
| Ambient temperature         | Thermometer                           | Input to emissions calculations.  |
| Lube oil temperature        | Local instrument                      | Engine performance monitoring.  |
| Lube oil pressure           | Local instrument                      | Engine performance monitoring   |

\*DAQ: Data Acquisition System.

Engine operating data, such as air manifold pressure, air manifold temperature, jacket water temperatures, etc., will be used to capture complete engine operating performance characteristics. These characteristics will be compared to data from different test runs at identical load points in order to validate the data in the final reported results.

In addition to obtaining passenger count from the operators' daily log, other parameters will be recorded to document the condition during each testing run:

1. Sea state.
2. Wind speed and direction.
3. Vessel heading and speed.
4. Vessel position or leg of route.
5. Vessel draft
6. Ambient conditions
7. Basic operating data from other engine as available from local instruments.

As the passenger ferry performs to actual field conditions, the emissions species data outlined in Section 3.1 will be captured simultaneously with engine performance data to develop an accurate, scientifically defensible profile of emissions data for this means of transportation.



### **3.3 Automobile Data Review**

As discussed in our previous report, a test of an automobile will not be performed, as sufficient and widely accepted data is available from various regulatory bodies. In order to obtain a defensible comparison, the automobile emissions rates will be determined based on the general routing of the transit bus to determine the automobile daily load profile and average number of trip miles. Next, based on information from the Department of Motor Vehicles for the county to be studied, the average vehicle gross weight and age data will be obtained for that county. This data, together with Corporate Average Fuel Economy (CAFÉ) standards for these size and vintage of vehicles will be used to generate a per passenger daily mass emission rate for comparison with results from the transit bus and passenger ferry.

### **3.4 Discussion**

During both the ferry and the bus tests, maximum effort will be extended to measure and record engine operating data for use in developing the emissions profile for the respective vehicles. The information is useful for data checks performed during the testing. Moreover, such data may also be used afterwards for comparison with data from the engine manufacturers to further validate the reduced test data.

## **4.0 TEST PROTOCOL DEVELOPMENT**

### **4.1 Objective**

The objective of this section is to develop protocols to determine emissions rate factors for the same passenger-commute for the marine and land based vehicles of a pollutant expressed in grams/BHP-Hr and normalized for vehicle rider-ship (i.e. grams/passenger/day).

### **4.2 Scope of Test Protocols**

The scope of the test program is to develop emissions rate factors for the same passenger-commute for the marine and land based vehicles of a pollutant expressed in grams/BHP-Hr and normalized for vehicle rider-ship (i.e. grams/passenger/day). The best available, laboratory-quality analyzers and test methods will be utilized to obtain accurate measurements of the emissions from the two sources to be tested. In addition, the same test methods, equipment and personnel will be used in both tests.

The following chemical species will be quantified:

- Acetaldehyde;
- Acrolein;
- Carbon4+ straight-chain hydrocarbons (aliphatic HCs, C<sub>4</sub> and larger);
- Carbon dioxide (CO<sub>2</sub>);
- Carbon monoxide (CO);
- Ethane;
- Ethylene;
- Formaldehyde and aldehyde compounds;
- Methane;
- Oxides of Nitrogen (NO<sub>x</sub>) (using NO + NO<sub>2</sub> on the FTIR);
- Oxygen (utilizing a paramagnetic analyzer);
- Particulate matter (utilizing ISO Method 8178)
- Sulfur dioxide (SO<sub>2</sub>);
- Water vapor (H<sub>2</sub>O); and
- Any other FTIR-detected species.

Total hydrocarbons (THC) will be derived from the FTIR speciated hydrocarbon data. Moisture, CO<sub>2</sub>, and O<sub>2</sub> will be reported in volume percent. Other gaseous emissions will be reported in parts per million by volume (ppmv), ppmv dry (ppmvd), ppmv corrected to 15% oxygen, and pounds per hour (lb/hr). Particulate emissions will be calculated in pounds per million Btu (lb/MMBtu), lb/hr, and grains per dry standard cubic foot (gdscf). Test runs will be of a duration based on source route data. One-minute averages will be collected for the instrumental FTIR method test runs.

The following methods will be used to determine these parameters in conformance with 40 CFR 60, “Standards of Performance for New Stationary Sources”.

**Table 4.1**  
**Parameters and Test Methods**

| <b>Parameter</b>  | <b>Method</b>  |
|---|--|
| Traverse Point Locations  | EPA Test Method 1 - <i>Sample and Velocity Traverses for Stationary Sources</i>  |
| Gas Composition, Oxygen (O <sub>2</sub> )   | EPA Test Method 3A - <i>Determination of Oxygen and Carbon Dioxide from Stationary Sources (Instrumental Analyzer Procedures)</i>                    |
| Volumetric Flow Rate  | EPA Method 19.<br><i>Actual fuel flow and intake airflow will be measured and summed as a data check for Method 19.</i>                              |
| Particulate   | ISO Test Method 8178 - <i>Determination of Particulate Emissions</i>   |
| Formaldehyde, Acetaldehyde, Acrolein, Water vapor (H <sub>2</sub> O), Carbon monoxide (CO), Carbon dioxide (CO <sub>2</sub> ), Oxides of Nitrogen (NO <sub>x</sub> ) (using NO + NO <sub>2</sub> on the FTIR), Sulfur dioxide (SO <sub>2</sub> ), Methane, Ethane, Propane, C4+ straight-chain hydrocarbons, Ethylene | EPA Test Method 320 - <i>Measurement of Vapor Phase Organic and Inorganic Emissions by Extractive Fourier Transform Infrared (FTIR) Spectroscopy</i> |
| THC, TNMHC  | THC & TNMHC will be derived from the FTIR speciated hydrocarbon data.  |
| Fuel Flow Measurement   | 40 CFR 92.107 “Fuel Flow Measurement”  |
| Intake Air Flow   | 40 CFR 92.108 “Intake Air and Cooling Air”   |
| Torque (Ferry only)   | ASME Power Test Code PTC-19.7  |

### **4.3 Testing Program and Description of Source**

The testing of each source will be conducted utilizing identical emissions test techniques and with the same test team. A description of the test procedures for each follows.

#### **4.3.1 Bus**

The candidate bus is a modern, passenger service bus operated by the Golden Gate Bridge Highway and Transportation District. The bus is powered by a four-stroke cycle, Detroit Diesel engine controlled by the DDEC Series IV electronic control system. The bus engine is fitted with Detroit Diesel’s low-emission controls equipment.

The bus emissions test will be preceded by pre-test, on-board data logging during a period of not less than one-week. During the pre-testing, test personnel will ride the bus, monitoring and recording vehicle and engine parameters including load (HP), speed, torque, operating temperatures and logging rider-ship. Monitoring will be performed using a laptop computer connected to the on-board Detroit Diesel Electronic Control (DDEC) system and operating the DDEC companion software program.

Based on the duty-cycle data gathered during the pre-test, the test team will operate the bus on a chassis dynamometer to duplicate the actual bus performance, including transients, while conducting the emissions testing. The test procedure will be as follows:

- Bus on Dynamometer.
- Discuss procedure with test team and driver.
- Review safety measures with all participants.
- Connect computer to DDEC system & establish communications.
- Install intake air mass flow meter.
- Install fuel oil supply / return metering system.
- Connect fuel flow and air flow transducers to data acquisition system.
- Mobile emissions laboratory set-up and calibrate.
- Begin Trial Test runs
- Commence Test Program
  - Steady-state data
    - 10-minute averages
    - Repeat each condition three-times and average data.
  - Transient Conditions
    - For each transient repeat three-times and average the data.
- Post Test Calibration.
- Uninstall test equipment.
- Bus returns to service.

#### **4.3.2 Ferry**

The Seaworthy team will perform all testing of the passenger ferry, M/V Mendocino, a new high-speed, multi-hull (catamaran), passenger vessel. The ferry is powered by four (4) identical Cummins KTA-50, sixteen-cylinder marine diesel engines which each drive a water-jet via a ZF Marine reduction gear. The engines are fitted with the engine manufacturer's electronic governing system.

All testing will be performed during normal service between Larkspur and San Francisco over a period of approximately three-days. Test equipment will be installed during the evenings or to coordinate with planned vessel maintenance activities to minimize impact on ferry operations or schedule.

The test procedure will be as follows:

- Discuss procedure with test team and crew.
- Review safety measures with all participants.
- Connect computer to engine control module & establish communications using the Cummins' "INSITE" software program.
- Install intake-air mass flow meter.
- Install fuel oil supply / return metering system.
- Install shaft torque meter.

- Connect fuel flow, torque meter and air flow transducers to data acquisition system.
- Mobile emissions laboratory set-up outside engine room and calibrate.
- Begin Trial Test runs / check equipment.
- Commence Test Program
  - Determine voyage average mass emissions rates (Dock to Dock)
  - Confirm Steady-state data
    - 10-minute averages.
    - Observe each condition three-times and average data.
  - Transient Conditions
    - For each transient observe three-times and average the data.
- Post Test Calibration.
- Uninstall test equipment.
- Ferry returns to service

#### **4.3.3 Schedule of Activities**

Testing on-site for each source will commence following the completion of pretest engine equipment checks. A list of activities by days is shown below.

**Table 4.2  
Test Agenda**

| <b>DAY</b> | <b>ACTIVITY</b>                              | <b>LAB<br/>AT-SITE</b> |
|------------|--|------------------------|
| 1          | INSTRUMENT SET-UP - BUS                      | NO                     |
| 2          | EMISSIONS MOBILE LAB SET-UP                  | YES                    |
| 3          | EQUIPMENT SET-UP, CALIBRATION AND TRIAL RUNS | YES                    |
| 4          | EMISSIONS TESTING                            | YES                    |
| 5          | EMISSIONS TESTING, POST-TEST CALIBRATION     | YES                    |
| 6          | DEMOBILIZATION                               | YES                    |
| 7          | INSTRUMENT SET-UP –FERRY                     | NO                     |
| 8          | INSTRUMENT SET-UP                            | NO                     |
| 9          | EMISSIONS MOBILE LAB SET-UP                  | YES                    |
| 10         | EQUIPMENT SET-UP, CALIBRATION AND TRIAL RUNS | YES                    |
| 11         | EMISSIONS TESTING                            | YES                    |
| 12         | EMISSIONS TESTING, POST-TEST CALIBRATION     | YES                    |
| 13         | DEMOBILIZATION                               | YES                    |

#### **4.4 Determination of Flue Gas Parameters**

##### **4.4.1 Stratification Check (Ferry Only)**

Prior to testing of the ferry engine, the FTIR operator may be directed to determine if stratification of the exhaust stream is present. Stratification is a variation in measured analyte

concentration as a function of the sample probe traverse position within the stack. Stratification is usually found in situations where two or more source streams are combined in a laminar (i.e., poorly mixed) manner ahead of the measurement point. If there is only one source stream, then it may indicate a leak of ambient air into the stack upstream of the measurement point with poor mixing. It is possible to observe stratification in a leak-free multi-cylinder internal combustion engine exhaust, if individual cylinder exhaust streams are (1) different in composition; and (2) exhibit laminar flow characteristics. Based on current experience, however, stratification is extremely rare in internal combustion engine exhaust streams.

The procedure to measure stratification is straightforward. A set of five 1-minute data points are measured by the FTIR at each of three (or greater) traverse points across the stack cross section. The number of traverse points depends on EPA Method 1 criteria (Appendix B), and will be determined once the stack diameter is known. A statistical comparison, analysis of variance (ANOVA), between the three (or greater) data sets for a selected analyte (e.g., formaldehyde) will be performed. ANOVA will reveal if there is a statistically significant difference between data sets. If the ANOVA test shows significant differences, then the percent difference between the lowest and highest value data sets is computed. If a statistically significant difference of greater than 5 percent between the lowest and highest points is found, then stack traversing using EPA Method 1 points must be conducted during sampling to obtain a representative sample. If a difference of less than 5 percent is found between traverse points, then subsequent sampling will be carried out with the probe tip located at the estimated centroid of the stack cross section.

An insignificant ANOVA result indicates no stratification is detected, and subsequent sampling is carried out with the probe tip at the estimated centroid of the stack cross section.

#### **4.4.2 Volumetric Flow Rate**

Exhaust flow rates for the engines will be determined by direct measurement of the inlet air and net fuel oil flows to cross-check EPA Method 19. Calculated average F-Factor values will be used in determining the exhaust gas flow rate based on individual fuel heat input rates and F-Factors.

#### **4.4.3 Oxygen Concentration**

Oxygen concentrations in the flue gas during each test run will be determined in accordance with procedures outlined in EPA Test Method 3A - *Determination of Oxygen and Carbon Dioxide Concentrations in Emissions from Stationary Sources. (Instrumental Analyzer Procedure)*. (Other relevant references are contained in Appendices B, C and D.)

Samples will be collected from a single point in the stack and transported to the mobile laboratory using a heat-traced sampling system. Further information about the sampling system is given in Section 6 of this test protocol.

#### **4.4.4 Determination of Stack Gas Moisture Content**

Stack gas moisture will be determined using EPA Test Method 320 (Appendix F), which is described in Section 6 of this test protocol. EPA Test Method 320 has been validated for moisture in gas-fired engines. This data is presented in a report published by the Gas Research Institute entitled, *Fourier Transform Infrared (FTIR) Method Validation at a Natural Gas-Fired Internal Combustion Engine*, GRI Document No. GRI-95/0271, December 1995.

#### **4.5 Particulate Matter Emissions Testing Using ISO Method 8178**

The test team will utilize a partial dilution tunnel-type sampling system from either Sierra Instruments or from AVL. The equipment provider will be selected once a test schedule has been established and will be based on equipment and operator availability. A number of different test methods and equipment types for the particulate sampling portions of this test program were investigated before deciding on the method described in this section. Background information and a topical discussion follow.

##### **4.5.1 Background**

Due to unique historical circumstances, the EPA has never published emissions test methods for stationary (or marine) Internal Combustion (IC) engines similar to 40CFR60 Method 20 for gas turbines. In the absence of such a rule, testers have typically utilized one of two separate sets of emissions testing methods, automotive/transport testing specifically for IC engines or generic stationary methods. A brief summary of each follows.

##### Automotive/Transport 40CFR86/89

Historically, the automotive/transport methods always included various load cycles and/or transient tests. Data Acquisition Systems (DAQ) and analyzers of the time lacked sufficient transient response, so samples were simply collected in bags at regular intervals to achieve a simple robust averaging method. This necessitated a cool sample to keep from damaging the (typically plastic) bag, so it became standard practice to dilute the full exhaust sample with fresh air to achieve a temperature of ~125°F or less. The dilution had many beneficial side effects:

- Prevented water condensation, eliminating the need for water knockouts.
- Permitted the use of atmospheric analyzers.

Once particulates were added to the testing, the dilution and cooling process caused aerosols and vapors to solidify - just as they would in the atmosphere. Consequently only a filter was needed to catch the particulates (or said another way, the particulates were defined as what could be caught with a filter).

##### Stationary Sources 40CFR60

Stationary source test methods presume the source operates at steady state, or that the rate of change is sufficiently slow that direct on-line sampling suffices. In addition, the large volume of exhaust flow precludes full dilution of the exhaust stream. Consequently, a small fractional portion of the exhaust is collected, and kept hot until it reaches a conditioning station where particulates are removed and water rapidly dropped out and removed. Sampling is then conducted generally cold and dry.

To accommodate particulates, EPA Method 5 requires the use of a separate manually traversed sampling probe to directly collect hot sample gas. The hot gas immediately passes through both a filter for particulates and canisters to condense the liquids, which have not yet solidified. At this time there is not a good correlation between Method 5 and the automotive dilution method.

#### Hybrid Approach

With the advent of high-speed data acquisition systems, many large engine testers have begun directly collecting a fractional sample and passing that through the analyzers, either hot and wet or cold and dry. This is particularly attractive where the tremendous volume of the exhaust precludes dilution.

However, to obtain data that better correlates with dilution tunnel measurements, several researchers have developed “partial dilution” methods specifically for particulates. These include Sierra Instruments in the USA and AVL in Europe. These methods extract a precisely measured isokinetic fraction of the exhaust flow and then dilute it similar to a full dilution tunnel. Depending on the specifics of the method, it would appear to more or less correlate with full dilution data, though this requires further investigation.

Rather interestingly, 40CFR94, the new test method for marine diesels, uses 40CFR92 (locomotive) test methods. This method permits partial dilution for particulate measurement, offering few specifics. Again much more information is needed.

In developing methods for the current protocol AETC recommends using 40CFR60 methods for gaseous components in conjunction with a good partial dilution sampling method for particulates.

#### **4.5.2 Principle of Operation**

Referring to Figure 4.1 on the following page, the dilution tunnel operates by drawing a known volume of exhaust from the stack and into the dilution tunnel where it is diluted with a known quantity of clean air. The fresh air keeps the exhaust gases cool and at the same times prevents moisture from condensing out of the exhaust stream. Some of the diluted air/exhaust mixture is then passed through a filter medium, which captures the particulate matter.

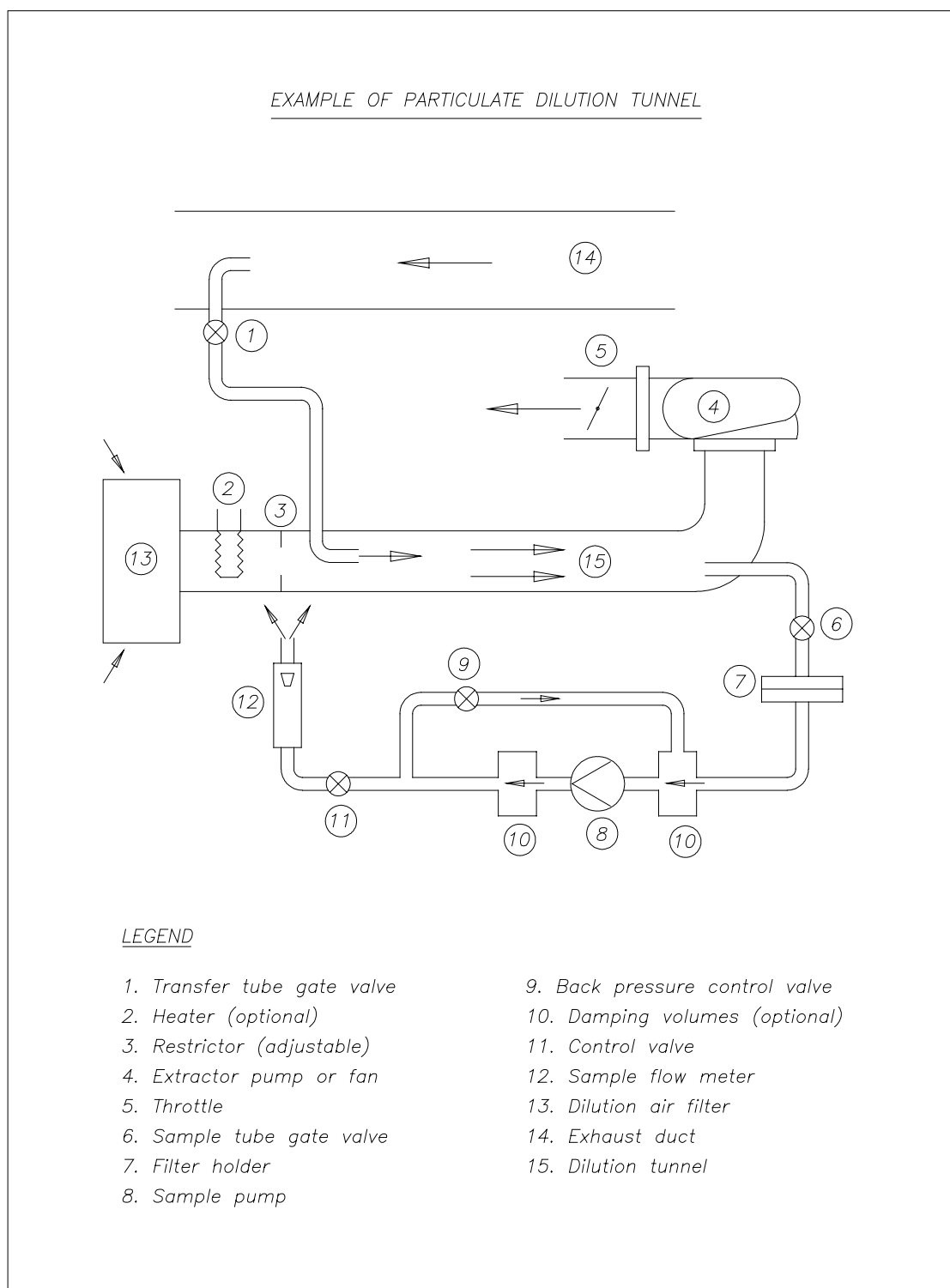
Filters are weighed before and after testing and the particulate matter concentrations in the exhaust system are then derived from the difference in the before and after weights. Appendices B and D of this protocol contain detailed descriptions of the sampling operation and the accuracies of the method.

#### **4.5.3 Sampling Equipment**

Detailed descriptions, certifications test reports and operating instruction manuals appear for the two partial dilution particulate sampling systems evaluated by AETC appear in AETC Report 4005.01.04, deliverable No. 4, “Emissions Test Equipment”.



**Figure 4.1**  
**Partial Dilution Sampling System**



## 4.6 Fourier Transform Infrared (FTIR) Spectroscopy Analysis

### 4.6.1 Introduction

The extractive FTIR measurement method is based on continuous extraction of sample gas from the stack, transporting the sample to the FTIR spectrometer and performing real-time spectral measurement of the sample gas. The sample gas spectra are analyzed in real time for target analytes, archived, and re-analyzed, if necessary, at a later date for other target analytes.

Our proposed FTIR subcontractor, Spectral Insights (SI), has conducted over 75 compliance tests using FTIR on natural gas-fired engines, using EPA Method 320 or equivalent. Each of these tests was completed successfully. In approximately 50 of the tests, corresponding EPA reference methods for THC, NO<sub>x</sub>, CO<sub>2</sub>, and CO were conducted simultaneously. The agreement between the methods was very good, except in cases where high levels of NO<sub>2</sub> were present. This was found to be due to low converter efficiency in chemiluminescent NO<sub>x</sub> analyzers. It was also determined at low NO<sub>x</sub> levels, the chemiluminescent analyzer is subject to fluorescence quenching due to CO<sub>2</sub>. FTIR is not subject to these known problems. The U.S. EPA has accepted all SI-collected FTIR data submitted to them without question, including NO<sub>x</sub> and CO data. (For further information on EPA's position on the use of FTIR for NO<sub>x</sub>, CO, and other species, please contact Ms. Rima Dishakjian at (919) 541-0443, Mr. Ken Durkee at (919) 541-5425, or Mr. Mike Toney at (919) 541-5247).

The proposed method will follow all of the procedures described in EPA Test Method 320. SI performed (as Radian Corporation) the successful EPA Method 301 FTIR validation test funded by the Gas Research Institute (GRI) in 1994. The validation was accepted by EPA, and EPA stated in a letter to GRI that FTIR can be used at any "gas-fired source". These data are reported in a document published by the Gas Research Institute entitled, *Topical Report: Fourier Transform Infrared (FTIR) Method Validation at a Natural Gas-Fired Internal Combustion Engine*, GRI Document No. GRI-95/0271, December 1995.

SI has conducted EPA Method 301 validation studies for the following compounds:

- Acetaldehyde;
- Acrolein;
- Carbon dioxide (CO<sub>2</sub>);
- Carbon monoxide (CO);
- Formaldehyde;
- Oxides of Nitrogen (NO<sub>x</sub>) (using NO + NO<sub>2</sub> on the FTIR); and
- Water vapor (H<sub>2</sub>O).

SI has successfully used FTIR to determine THC and TNMHC data from engines. These components of engine exhaust are primarily methane (CH<sub>4</sub>), ethane, ethylene, and formaldehyde. Because FTIR can measure these species separately, it is straightforward to measure THC and TNMHC using the FTIR system by adding the concentration of the appropriate species, either un-weighted, or carbon-weighted. Because the usual detector used in Method 25A analysis is a flame ionization detector (FID), the measurement of THC can be biased with the varying relative responses for each hydrocarbon. However, because THC in the engine exhaust is primarily

methane, the differences between THC by FID and FTIR are typically negligible. TNMHC determination has historically been difficult using M25A, due to the high levels of methane expected to be present in the effluent gas and the difficulty of selectively removing methane. A recent EPA-sponsored test of Internal Combustion (IC) engine exhaust measurements at Colorado State University using a "TNMHC" analyzer showed the difficulties with attempts to remove high (1000 ppm) levels of methane.

#### 4.6.2 Summary of FTIR Method

FTIR measurement is based on the absorbance of infrared energy by gas phase compounds. Most molecules absorb infrared energy at characteristic frequencies based on the molecular vibrational and/or rotational motion within the molecule. The absorption characteristics of a particular compound can be used to identify and quantitate the concentration of that compound. The concentration of a single target compound is related to its absorbance according to Beer's Law:

$$A(\nu) = a(\nu)bc$$

Where:

$$\begin{aligned} A(\nu) &= \text{absorbance at wavelength } \nu, \\ a(\nu) &= \text{absorption coefficient at wavelength } \nu, \\ b &= \text{path-length, and} \\ c &= \text{concentration.} \end{aligned}$$

If more than one compound absorbs light at a given wavelength, then the total absorbance is found from a linear combination of Beer's Law for each compound.

Where:

$$A_{\text{total}}(\nu) = b \sum_{i=1}^N a_i(\nu) c_i$$

$$\begin{aligned} A_{\text{total}} &= \text{total absorbance at wavelength } \nu_i, \\ a_i(\nu) &= \text{absorption coefficient for compound I at wavelength } \nu, \\ c_i &= \text{concentration of compound I,} \\ N &= \text{total number of absorbing compounds, and} \\ b &= \text{path-length.} \end{aligned}$$

Compounds with very sharp spectral features, such as CO, can exhibit nonlinear analyzer response, requiring correction algorithms to accurately calculate concentrations. Correction algorithms are generated by measuring the spectrum of the compound at several different concentrations and fitting the resulting data to an appropriate correction curve.

Quantitation of each target compound is based on the application of a reference spectrum that is specific to that compound and is measured at a known concentration, temperature, and pressure. For the target compounds, quantitation is performed by selecting characteristic absorbance regions that have minimal interferences from other compounds present in the gas stream.

The classical least squares (CLS) method is applied to fit the reference spectra to the sample spectrum, with the resulting scaling factors used to calculate concentrations. The CLS method finds the set of concentrations that minimizes the residuals in the analysis region and provides a confidence interval for each concentration calculated. The confidence interval is used as a diagnostic to determine how well the CLS method fit was accomplished. It is used to assess instrument performance and to alert the user to review the data for the presence of new or elevated concentrations of interferants in the sample.

#### 4.6.3 Analytes {tc "7.3      Analytes " | 2}

The analytes that will be measured by this method and their CAS numbers are shown below.

**Table 4.3**  
**Target Analytes**

| Compound                            | Chemical Abstract Number |
|-------------------------------------|--------------------------|
| Acetaldehyde                        | 75-07-0                  |
| Acrolein                            | 107-02-8                 |
| C4+ straight-chain hydrocarbons     | NA                       |
| Carbon dioxide (CO <sub>2</sub> )   | 124-38-9                 |
| Carbon monoxide (CO)                | 630-08-0                 |
| Ethane                              | 74-84-0                  |
| Ethylene                            | 74-85-1                  |
| Formaldehyde                        | 50-00-0                  |
| Methane                             | 74-82-8                  |
| Nitrogen dioxide (NO <sub>2</sub> ) | 10102-44-0               |
| Nitric oxide (NO)                   | 10102-43-9               |
| Propane                             | 74-98-6                  |
| Sulfur dioxide (SO <sub>2</sub> )   | 7446-09-5                |
| Water vapor (H <sub>2</sub> O)      | 7732-18-5                |

#### 4.6.4 Applicability

This method applies to the analysis of vapor phase organic or inorganic compounds that absorb energy in the mid-infrared spectral region, about 400 to 4000 cm<sup>-1</sup> (25 to 2.5 um). This method is used to determine compound-specific concentrations in a multi-component vapor phase sample that is contained in a closed-path gas cell. Spectra of samples are collected using double beam infrared absorption spectroscopy. A computer program is used to analyze spectra and report compound concentrations.

#### 4.6.5 Method Range and Sensitivity {tc "7.5      Method Range and Sensitivity " | 2}

Range and sensitivity of the method are functions of the following factors:

- Measurement cell path-length;
- Absorption coefficient of each target compound at the selected analytical frequency region;
- Spectral resolution;

- Interferometer sampling time;
- Number of individual interferograms used to produce each time-averaged spectrum;
- Detector sensitivity and response time;
- Compounds comprising the sample matrix; and
- Biases due to the sample collection and/or analysis system.

Measurement cell path-length is the primary determinant of the range and sensitivity of the method. Appropriate path-length of the measurement cell will be determined by considering the following:

- The lowest expected concentration or the desired target detection limit of each target compound; and
- The expected concentration of any potential interfering compound.

#### 4.6.6 Performance Specifications

Prior to the performance of the work, the performance specifications shown below will be verified with the FTIR instrumental configuration anticipated for this program.

**Table 4.4**  
**FTIR Method Performance Specifications {tc "7-2**

#### Method Performance Specifications " \f D }<sup>a</sup>

| Compound                                     | Detection Limit |
|--|-----------------|
| Acetaldehyde                                 | 1.0 ppmv        |
| Acrolein                                     | 1.0 ppmv        |
| C4+ straight-chain hydrocarbons <sup>b</sup> | 0.1 ppmv        |
| Carbon dioxide (CO <sub>2</sub> )            | <0.04%          |
| Carbon monoxide (CO)                         | 0.1 ppmv        |
| Ethane                                       | <1 ppmv         |
| Ethylene                                     | 0.1 ppmv        |
| Formaldehyde                                 | 0.2 ppmv        |
| Methane                                      | <5 ppmv         |
| Oxides of Nitrogen (NO <sub>x</sub> )        | <5 ppmv         |
| Propane                                      | <1 ppmv         |
| Sulfur dioxide (SO <sub>2</sub> )            | <5 ppmv         |
| Water vapor (H <sub>2</sub> O)               | <0.1%           |

<sup>a</sup> Precision (% RSD) and Accuracy (% bias) equal to  $\pm 10\%$  and are defined at concentrations 10 times greater than the analyte detection limit.

<sup>b</sup> Reported as hexane equivalents.

#### **4.6.7 FTIR Sampling Equipment {tc "7.7 FTIR Sampling Equipment " \l 2}**

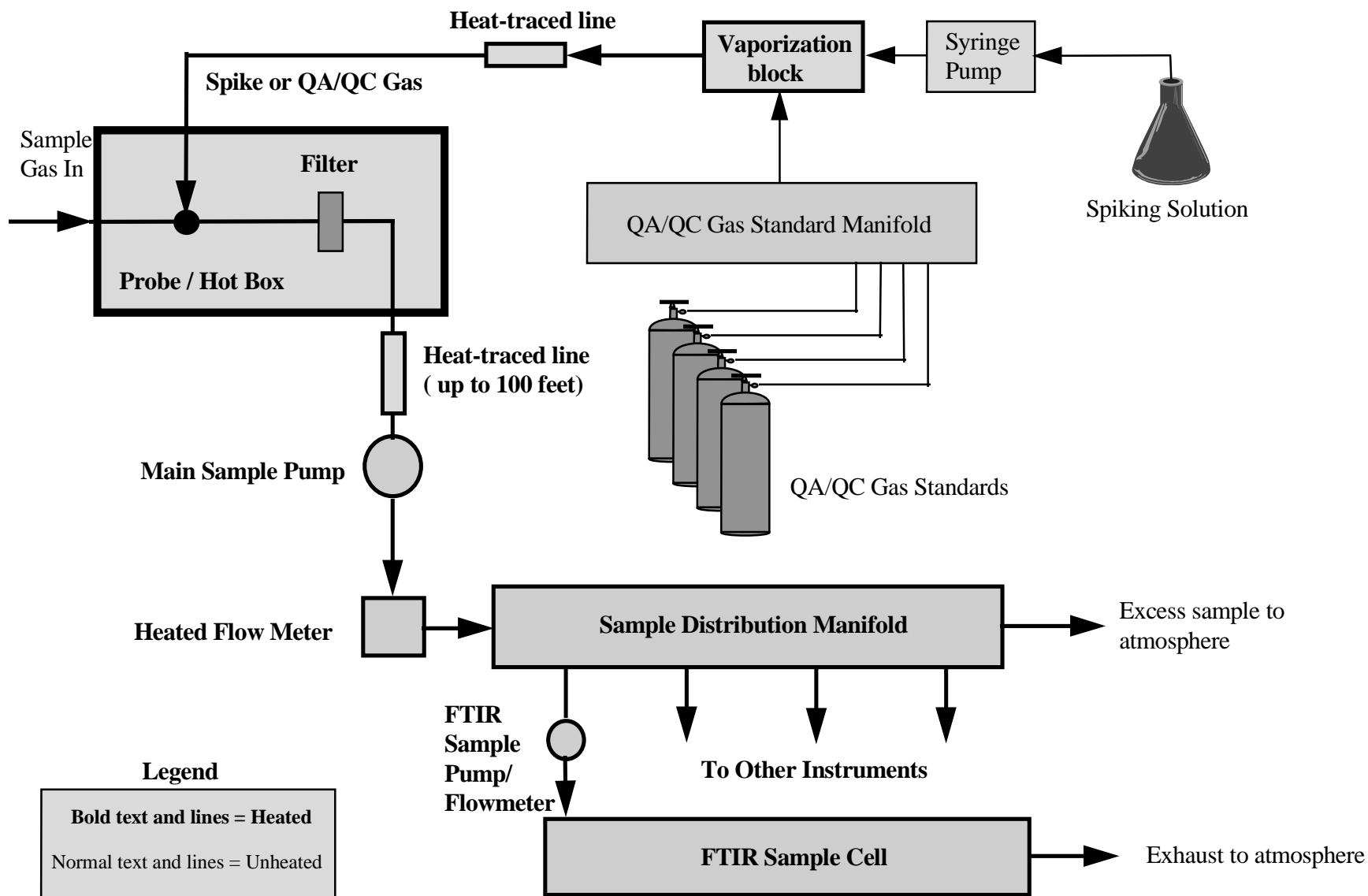
The sampling and measurement system consists of the following components:

- Heated probe;
- Heated filter;
- Heat-traced Teflon<sup>®</sup> sample line;
- Teflon<sup>®</sup> coated, heated-head sample pump;
- FTIR spectrometer; and
- QA/QC apparatus.

The following Figure 5.1 illustrates the FTIR sampling and measurement system. In operation at any source, the sample is continuously extracted from the stack through the heated probe. Sample gas is then sent into a heated filter assembly, which will remove any particulate matter from the sample stream to protect the remainder of the sampling and analysis system. The probe liner and filter body are made of glass, and the filter element is polytetrafluoroethylene. In addition to providing an inert surface, the glass filter holder allows the operator to observe the filter loading during sampling operations. The probe and filter are contained in a heated box, which is mounted on the stack and maintained at a temperature of 250 °F.

After passing through the filter assembly, the sample gas is transported to the FTIR spectrometer by a primary heat-traced PTFE sample line maintained at 250 °F driven by a heated- PTFE head sample pump maintained at approximately 204° C (400° F). The sampling flow rate through the probe, filter, and sampling line is a nominal 20 standard LPM. Sample gas then enters an atmospheric pressure heated PTFE distribution manifold where it is sent to the FTIR spectrometer via a slipstream flowing at 9 LPM. Another slipstream from this manifold supplies sample to the oxygen analyzer for EPA Test Method 3A analyses. Excess sample gas not used by instruments is vented to atmosphere.

FTIR spectrometer sample gas is taken from the distribution manifold by a secondary heated PTFE head sample pump maintained at approximately 204° C (400° F) and directed into the FTIR sample cell maintained at 185° C (365° F) for real-time analysis. The cell is made of nickel-plated aluminum, with gold-plated glass substrate mirrors and potassium chloride windows. Exhaust gas from the cell is vented to the atmosphere.



**Figure 4.2**  
**FTIR Sampling and Measurement System**

#### 4.6.8 Preparation for Sampling {tc "7.8 Preparation for Sampling " \l 2}

Before commencement of daily sampling operations, the following tasks will be carried out:

- System leak check;
- Measurement of FTIR background spectrum;
- Instrumental QC; and
- Sampling and measurement system QC spike run.

Detailed descriptions of these tasks are presented in the paragraphs below.

The heated sampling lines, probes, and heated filter will be positioned at the inlet and outlet locations. All heated components will be brought to operating temperature, and a leak check of both inlet and outlet sampling systems is performed. The leak check will be performed by plugging the end of the probe and watching the main sample flow meter to see that the value goes to zero.

A background spectrum is measured using zero air or zero nitrogen through the cell. Next the QC gases are measured by flushing the cell and they must agree to within a percentage of target value. The QC gases used for this program include (with acceptance criteria):

- Carbon monoxide (CO) used for frequency calibration. Carbon monoxide is directly injected into the sample cell to measure photometric accuracy, validity of the non-linear correction algorithm and serve as a frequency (i.e., wavelength) calibration. Acceptable limits for CO standard analysis are  $\pm 6$  percent of certified concentration; and
- Methane/nitric oxide/carbon dioxide mixture, used for overall system performance check (calibration transfer standard) (acceptance limits are  $\pm 6\%$  of the certified concentration).

These two mixtures are typically combined into one mixture. The gas standards are also known as calibration transfer standards, as described in EPA Test Method 320.

The sampling and measurement system spike test will be used to perform validation and directly challenge the complete system and provide information on system accuracy and bias. Dynamic analyte spiking involves injecting a known concentration of spike analyte at the probe exit and looking for an appropriate instrument response. Formaldehyde will be used as a surrogate for all target analytes. Formaldehyde is selected as the surrogate due to its potential difficulties in sampling. While this procedure can be performed for  $\text{NO}_x$  and CO, experience has shown that the direct instrumental challenges are sufficient for those species. While it is certainly possible to perform spikes for  $\text{NO}_x$  and CO, this would add to the cost of the program by obtaining an additional gas standard containing  $\text{NO}_x$ , CO and a sulfur hexafluoride tracer (to determine dilution) as well as approximately 30-45 minutes per day extra to perform the spikes before and after the day's testing. The standard must contain 10 times the usual concentration of the target species because the spike gas will be diluted by at least a factor of 10, according to EPA Method 320.



This test is conducted to satisfy the requirements set in EPA Test Method 320. Section 6, Equipment and Supplies, of Method 320 gives a description of the dynamic spiking apparatus. FTIR has been validated for the compounds listed in Section 6.1 of this test protocol.

The FTIR spiking procedure used will be the following:

- Measure native stack gas for a 3 minute period (i.e., 3-1 minute samples);
- Start spike gas flow into sample stream, upstream of the heated filter;
- Let system equilibrate for at least 2 minutes;
- Measure spiked sample stream for 3 minutes (i.e., 3 - 1 minute samples); and
- Turn off spike gas flow.

The above procedure will produce 3 spiked/unspiked sample pairs. Spike recovery and relative standard deviations for 3 spiked/unspiked sample pairs will be computed from the procedure given in Sections 8.6.2 and 9 of EPA Method 320. The recovery must be 70-130% for the system to be considered acceptable for testing.

The spiked/unspiked pairs will not be recorded simultaneously, because only one FTIR system will be available for this test program. This procedure should produce acceptable results because previous experience indicates that this type of source is very stable for a given operating condition.

#### **4.6.9 Sampling and Analysis {tc "7.9 Sampling and Analysis " \l 2}**

FTIR sampling will be performed simultaneously with EPA Test Method 3A and ISO Method 8178 (particulates) during the testing. The start and stop times of the PM method will be coordinated with the FTIR operator, so that FTIR data files can be coordinated with method 8178 start and stop times. FTIR sampling will be accomplished using a heated transfer line.

Typical FTIR operating conditions are shown below. These parameters provide the detection limits given previously in section 5.6. Some of these parameters are sample matrix dependent.

**Table 4.5**  
**Typical FTIR Operating Parameters**  
**{tc "7-3**

#### **Typical FTIR Operating Parameters " \f D }**

| <b>Parameter</b>                        | <b>Value</b>                        |
|---|-------------------------------------|
| Spectral Range (cm <sup>-1</sup> )      | 400 - 4000                          |
| Spectral Resolution (cm <sup>-1</sup> ) | 0.5 (or better)                     |
| Optical Cell Path length (m)            | 3.4 (variable -- 1-10)              |
| Optical Cell Temperature (°C)           | 185                                 |
| Sample Flow Rate (liters/minute)        | 9 (3.0 optical cell volumes/minute) |
| Integration Time (minutes)              | 1 (Average of 43 spectra)           |

Sample flow rate will be determined by the data averaging interval and FTIR spectrometer sample cell volume. A minimum of 3 sample cell volumes of gas must flow through the system to provide a representative sample during a single integration period. Typically, a 1 minute averaging period with a 3 liter volume sample cell gives a minimum flow rate of 9 LPM. Typically a flow rate of 20 standard LPM is used to accommodate the FTIR and EPA Test Method 3A instrumentation on-site, and to minimize sample residence time in the sampling system.

The temperature of all sampling system components will be at a minimum of 250 °F to prevent condensation of water vapor or other analytes in the sampling system. Actual sampling system operating temperatures will be determined before start of testing. The FTIR sample cell temperature will be maintained at 365 °F (185 °C) to ensure that condensation of high-boiling point analytes on the cell optics is minimized.

FTIR sample cell pressure will be monitored in real-time in order to calculate analyte concentration in parts-per-million. The cell is normally operated near atmospheric pressure with the cell pressure continuously monitored.

Stack gas temperature will also be monitored to provide information on potential sample analyte condensation in the sampling system. If the stack gas temperature is higher than the lowest sampling system component temperature, then an assessment by the spectroscopist or field team leader must be made whether any analytes of interest may condense within the sampling system, resulting in measurement bias.

Sampling probe location will be determined by the requirements set in EPA Method 1 in terms of duct diameters upstream and downstream of disturbances. Sampling and analysis procedures are straightforward for a single-source measurement. Once QA/QC procedures have been completed at the beginning of a test day, the sample will be allowed to flow continuously through the FTIR spectrometer cell and the software will be instructed to start spectral data collection. The spectrometer collects one interferogram per second and averages a number of interferograms to form a time-integrated interferogram. Typical averaging times range from 1 to 5 minutes. The interferogram is converted into a spectrum and analyzed for the target analytes. After spectral analysis, the spectrum is stored on the computer and later permanently archived. Spectral data collection is stopped after a pre-determined time, corresponding to a “run”. Typical runs will be 1 hour long, giving 60 1-minute averaged points for each target analyte. At the end of the test day, the end-of-day QA/QC procedures are conducted.

Correction of all target analyte (except water) concentrations to a dry basis will be made using the following equation:

$$\text{Dry} = \frac{\text{Wet}}{1 - (\text{H}_2\text{O}/100)}$$

Where:

- Dry = Corrected dry concentration of the target analyte;
- Wet = Measured concentration of the target analyte on a wet basis, at a specific point in time;
- H<sub>2</sub>O = Corresponding measured concentration of H<sub>2</sub>O (in percent).

Before any testing is started at a given site, an initial “snapshot” of the stack gas is taken with the FTIR measurement and analysis system to determine the true sample matrix. If any target analytes are present at significantly higher levels than expected, adjustments will be made to the cell path length and/or the spectral analysis regions used for quantitative analysis. These adjustments will minimize interferences due to unexpectedly high levels of detected analytes.

FTIR method performance is gauged from the results of the QA/QC procedures given in Section 9, Quality Control, of EPA Test Method 320. Acceptable spiking tests will meet acceptance criteria of 70 to 130 percent recovery. The acceptable instrument diagnostic and system response check accuracy will be within  $\pm 6$  percent of target. Acceptable system response check precision will be 6 percent RSD.

Quantitative analysis is performed by a mathematical method called multi-variate least squares (commonly known as Classical Least Squares or CLS). CLS constructs an optimized linear combination (or ‘fit’) of the reference spectra to duplicate the sample spectrum, utilizing the Beer-Lambert Law. The Beer-Lambert Law states that the absorbance of a particular spectral feature due to a single analyte is proportional to its concentration. This relationship is the basis of FTIR quantitative analysis. The coefficients of each compound in the linear fit yield the concentration of that compound. If it is found that the quantitative analysis of a given compound responds non-linearly to concentration, a calibration curve is developed by measuring a series of reference spectra with differing optical depths (concentration times path length) and using them in the linear fit. Low molecular weight species such as water vapor and carbon monoxide require non-linear correction, possibly even at levels as low as 100 ppm-meters (concentration times path length). Analytes greater than 50-60 amu molecular weight usually do not require non-linear corrections. An experienced spectroscopist can determine whether non-linear corrections are necessary for an analyte in a given source-testing scenario.

The SI validated spectral database includes the compounds shown below. These spectra were validated in the laboratory at a cell temperature of 185° C against certified gaseous standards. Any compounds identified in the stack gas and not included in the SI database can be quantified if necessary after subsequent laboratory reference spectrum generation.

**Table 4.6**  
**Available Reference Compound FTIR Spectra {tc "7-4**

**Compounds for Which Reference FTIR Spectra**  
**Are Available in the SI Spectral Library " \f D }<sup>a</sup>**

|                 |                      |                    |
|-----------------|----------------------|--------------------|
| 1-butene        | chlorobenzene        | methylene chloride |
| 1,3-butadiene   | <i>cis_2</i> _butene | <i>n</i> _butanol  |
| 2-methylpropane | cyclohexane          | <i>n</i> _butane   |
| 2-propanol      | cyclopentane         | <i>n</i> _pentane  |

|                     |              |                  |
|---------------------|--------------|------------------|
| 2-methoxyethanol    | cyclopropane | nitric oxide     |
| 2-methyl-2-propanol | ethane       | nitrogen dioxide |
| 2-methylbutane      | ethylbenzene | nitrous oxide    |
| 4-vinylcyclohexane  | ethylene     | <i>o</i> _cresol |

|                  |                     |                        |
|------------------|---------------------|------------------------|
| Acetaldehyde     | formaldehyde        | <i>o</i> _xylene       |
| acetic acid      | hexanes             | <i>p</i> _cresol       |
| acetone          | hydrogen fluoride   | <i>p</i> _xylene       |
| Acetylene        | hydrogen chloride   | phenol                 |
| acrolein         | isobutylene         | propane                |
| ammonia          | <i>m</i> _xylene    | propylene              |
| benzene          | <i>m</i> _cresol    | styrene                |
| carbon monoxide  | methane             | sulfur dioxide         |
| carbon dioxide   | methanol            | toluene                |
| carbonyl sulfide | methyl ethyl ketone | <i>Trans</i> -2-butene |
|                  |                     | water vapor            |

<sup>a</sup> Spectra were collected at a cell temperature of 185<sup>o</sup> C.

#### **4.6.10 FTIR Analytical Uncertainty and Detection Limits**

FTIR analytical uncertainty for each analyte will be reported in real-time by the FTIR quantitative analysis software. After each run, the estimated detection limits for each analyte of interest can be computed. These real-time calculations exceed the requirements set in Method 320, since they are actual values in the presence of the real sample matrix, not estimates as computed in the method.

#### **4.6.11 FTIR Method Data Review Procedures**

The following procedure will be conducted to review and validate the FTIR data.

##### Post-test Data Review procedure (on-site)

1. Examine the concentration vs. time series plot for each compound of interest, and identify regions with the following characteristics:
  - sudden change in concentration;
  - unrealistic concentration values;
  - significant changes in 95 percent confidence intervals reported by software; and

- sudden increase of noise in data.
- 2. Select representative spectra from the time periods indicated from Step 1.
- 3. Subtract from each representative spectrum chosen in Step 2 a spectrum, which was taken immediately prior in time to the indicated time region.
- 4. Manually quantitate (including any non-linear corrections) for the species in question and compare the result to the difference in software-computed concentrations for respective spectra.
- 5. If concentration values in Step 4 do not agree to within 5 percent, determine whether the difference is due to a recoverable or non-recoverable error.
- 6(i). If the error is non-recoverable, the spectra in the indicated time region are declared invalid.
- 6(ii). If the error is recoverable, and time permits, determine possible source(s) of error and attempt to correct. If time is critical, proceed with measurement. If correction is achieved, conduct QA/QC checks before continuing.
- 7. Determine the peak-to-peak scatter or the root mean square (RMS) noise-equivalent-absorbance (NEA) for the representative spectra.
- 8. If the NEA exceeds the limits required for acceptable detection limits, the spectra in the time region are declared invalid (due to non-recoverable error).
- 9. Data found invalid are subject to re-measurement.

*Final Data Review (off-site) ftc "7.11.2*

*Final Data Review (off-site) " \l 3}*

The procedures for final data review include those given above; however, if a non-recoverable error is found during this phase, the data are considered invalid. In addition, the following procedures will be carried out by the spectroscopist to perform a final data validation:

1. If any recoverable data errors are detected from the procedure, determine the cause and perform any necessary corrections.
2. For analytes which were not detected or detected at low levels:
  - i. Estimate detection limits from validated data;
  - ii. Check for measurement bias.

**4.6.12 FTIR QA/QC Procedures ftc "7.12 FTIR QA/QC Procedures " \l 2}**

The FTIR QA/QC apparatus will be used to perform two functions:

- Dynamic analyte spiking; and
- Instrumental performance checks.

Dynamic analyte spiking is used for quality control/quality assurance of the complete sampling and analysis system. Dynamic spiking is continuous spiking of the sample gas to provide information on system response, sample matrix effects, and potential sampling system biases. Spiking is accomplished by either:

- Direct introduction of a certified gas standard; or
- Volatilization of a spiking solution.

Certified gas standards are preferred due to simplicity of use, but many target analytes cannot be obtained as certified gas standards, and must be spiked using standards generated by volatilized solutions.

Gaseous spiking is carried out by metering the spike gas into the sample stream at a known rate. Spike levels are calculated from mass balance principles. When certified gas standards are used, a dilution tracer, such as sulfur hexafluoride, is used to directly measure the fraction of spike gas spiked into the sample. This technique can be used instead of mass balance calculations.

FTIR method performance is gauged from the results of the QA/QC. EPA Test Method 320 instructs the user to determine the percent spike recovery of 3 pairs of spiked/unspiked samples. EPA Test Method 320 acceptance criterion is 70 to 130 percent recovery for the three pairs of samples. The acceptable instrument diagnostic and system response check accuracy will be within  $\pm 6$  percent of target. Acceptable system response check precision will be 6 percent RSD.

#### **4.7 Sampling Locations**

Sample locations were selected based on obtaining the most representative samples by meeting the requirements of EPA Method 1, *Sample and Velocity Traverses for Stationary Sources*. As indicated in Section 4.0, a stratification check at the ferry engine sampling location will be performed prior to commencement of testing to confirm the suitability of the sample location. The small diameter of the bus exhaust system precludes this test for the bus.

##### **4.7.1 Bus**

Downstream of the turbocharger a special collar / stack extension section will be installed to accommodate both the particulate and FTIR (heated) sampling probes.

##### **4.7.2 Ferry**

In engine room, five (5) pipe diameters downstream of the turbocharger outlet.

#### **4.8 Site Requirements**

Sample ports will be designed, fabricated and installed during pre-test set-up and prior to the mobilization of the emissions laboratory. The facilities will provide either 240 volts at 40 amperes (single phase) or 480 volts at 20 amperes (single or three-phase) power at each engine location.

The mobile laboratory will be located adjacent to the bus and in the case of the ferry will be set-up near the entrance to the engine room on the main deck so that no more than 100 feet of heat-traced sample line will be required for the FTIR sampling train.

It will also be necessary for the bus and ferry operating personnel to assist with starting, stopping and normal operation of the engines as required during the test program.

#### **4.9 Quality Assurance Program**

The quality assurance effort to be implemented as part of this test program will incorporate both quality assurance and quality control. Quality control (QC) is a system of routine technical activities implemented by the project team personnel to measure and control the quality of the data as it is collected and manipulated. QC activities include technical reviews, accuracy checks,

and the use of standard procedures for data collection, analysis, and reporting. Quality assurance includes those activities that provide an independent assessment of a project or project tasks, including quality control functions. The Quality Assurance Coordinator assigned to this project will be responsible for coordinating the development and execution of QA/QC activities in all phases of the project and will supervise and check data collected from the Method 8178 equipment as well.

The Seaworthy project team will conduct all QA/QC procedures specified in the EPA test methods.

## **4.10 Safety**

### ***4.10.1 Responsibilities***

This section of the field test plan describes the general health and safety requirements for field work. Test personnel will also abide by all safety measures administered by the facility.

#### ***4.10.1.1 On-Site***

The person responsible for implementing and ensuring compliance with the health and safety requirements during the on-site testing is the FTIR Project Manager. All supervisors are responsible for ensuring that assigned employees and their subcontractors under their direction comply with the requirements. All employees and subcontractors on-site are responsible for complying with the requirements and those of the host facility. Each Test Team member reads and signs a copy of the safety plan prior to arrival on-site.

#### ***4.10.1.2 Authorities***

The Project Manager and Test Team Leaders will have the authority to upgrade the requirements of this plan if, in either's judgment, such adjustments are necessary and will complete the following Project Health and Safety Sign-Off Sheet prior to the initiation of the testing program.

The designated representative at the test facility (ferry or dynamometer operator) also has the authority to impose additional constraints or to waive particular facility Health and Safety restrictions.

## Project Health and Safety Sign-Off Sheet

Project Number/Title: \_\_\_\_\_

Location: \_\_\_\_\_

### CHECK ONE



#### NO PROJECT SPECIFIC HEALTH AND SAFETY PLAN REQUIRED

RATIONALE: \_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

Project Manager: \_\_\_\_\_

Date: \_\_\_\_\_

Health and Safety Officer: \_\_\_\_\_

Date: \_\_\_\_\_



#### PROJECT SPECIFIC HEALTH AND SAFETY PLAN REQUIRED

**CERTIFICATION:** Spectral Insights and its subcontractors will conduct the activities specified in the contract and/or work assignment in accordance with the approved Health and Safety Plan unless instructed otherwise by the authorized Health and Safety Officer.

I certify that I have read, understood, and if applicable, approved the Health and Safety requirements in the Health and Safety plan cited above.

Project Manager: \_\_\_\_\_

Date: \_\_\_\_\_

Health and Safety Officer: \_\_\_\_\_

Date: \_\_\_\_\_

Project Team Members:

\_\_\_\_\_

Date: \_\_\_\_\_

\_\_\_\_\_

Date: \_\_\_\_\_

\_\_\_\_\_

Date: \_\_\_\_\_

\_\_\_\_\_

Date: \_\_\_\_\_

\_\_\_\_\_

Date: \_\_\_\_\_

\_\_\_\_\_

Date: \_\_\_\_\_

\_\_\_\_\_

Date: \_\_\_\_\_

Project Manager:

Distribute completed, signed copies of this form to:  
Project File

**Figure 4.3**  
**Project Health and Safety Sign-off Sheet**



#### 4.10.2 Site Entry

At the start of each day of sampling, the on-site team leader or his designee informs the plant contact of the test crew arrival.

#### 4.10.3 Hazard Analysis

##### 4.10.3.1 Physical Hazards

The physical hazards expected to be encountered in performing the sampling tasks are discussed below.

##### Falls

If test personnel are required to work on sampling platforms during the sample collection phase of this project, the platforms and their access ladders present fall hazards. All platforms will have handrails and safety harnesses will be used as necessary.

##### Heat

Source sampling tasks involve collecting samples from hot flue gases. The ducts covering these gases and the probes used to sample them present the hazard of thermal burns. It is expected that the stack gas temperature will exceed 500°F. Working in elevated ambient temperatures has the potential for causing heat stress. Regular work breaks will be enforced as the ambient working conditions dictate. Ambient temperatures are expected to not exceed 95°F during the daytime.

##### Electrical

The use of electrical equipment, particularly portable equipment and extension cords, often poses electrical shock hazards. Furthermore, work at heights may require working in close proximity to power lines.

##### Noise

The potential for overexposure to noise will exist at locations near the engines.

##### Fire

Flammable reagents are the primary fire hazard. The facility may also have areas where ignition sources are prohibited.

##### 4.10.3.2 Chemical Hazards {tc "11.3.2 Chemical Hazards " \l 3}

In addition to the analytes expected in the flue gas, several chemicals are used for QA/QC purposes. The table below contains a list of the known chemical hazards.

**Table 4.7**  
**Chemical Hazards {tc "11-1**  
**Chemical Hazards " \f D }**

| Exposure Location | Chemical       |
|-------------------|----------------|
| Sample Collection | Acetone        |
|                   | Carbon dioxide |

| Exposure Location | Chemical               |
|-------------------|------------------------|
|                   | Carbon monoxide        |
|                   | Formaldehyde           |
|                   | Methane                |
|                   | Nitric oxide           |
|                   | Total mass particulate |

The Material Safety Data Sheets (MSDS) for chemicals kept at the test location are listed below:

- Acetone;
- Carbon dioxide;
- Carbon monoxide;
- Methane;
- Nitric oxide;
- Nitrogen, compressed; and
- Nitrogen, liquefied.

Ambient air monitors are maintained in the mobile laboratory to monitor the following:

- PPM levels of SO<sub>2</sub> and NO;
- Percent O<sub>2</sub>;
- PPM levels of CO; and
- Percent lower explosive limit (LEL).

#### **4.10.4 Hazard Abatement {tc "11.4 Hazard Abatement " \l 2}**

This section describes the general requirements for hazard abatement.

##### 4.10.4.1 Physical Hazard Abatement

##### {tc "11.4.1 Physical Hazard Abatement " \l 3}

##### Fall Prevention

Inspection of the scaffolding and platforms is required before any are used. If the sampling platforms are unstable or structural defects are detected, measures must be taken to correct the problem prior to platform loading. When accessing elevations, no more than one person is to climb access ladders at a time.

##### Burn/Heat Stress Prevention

Hot sampling probes are handled only by persons wearing heat-insulating gloves. Personnel monitor each other for signs of heat stress: profuse perspiration, cool or pale skin, dizziness, or nausea. Affected individuals should rest in a cool area and sip cool water or electrolytes. If symptoms of heat stroke, such as hot, dry skin or unconsciousness appear, obtain medical attention immediately.

### Electrical Shock Prevention

Field crewmembers should be constantly aware of the position of power lines and cords relative to themselves and their electrical equipment in use to prevent electric shock. All equipment that is not required to operate overnight is left unplugged. The use of power strips with multiple outlets is limited to strips with internal circuit breakers. All cord connections are secured so there is no direct stress on joints or terminal screws. All electrical sampling equipment is properly grounded to reduce electrical hazards. The cord connections are manually disconnected from the power source prior to any work that allows direct access to potentially energized parts.

### Noise Exposure Control

Test personnel wear hearing protection when working in areas that are either designated as requiring protection or in areas where they must raise their voices to converse with someone no more than three feet away. Earplugs are provided to all sampling personnel.

### Fire Prevention

In areas where flammable materials are stored or in use, no ignition sources, including smoking, are permitted. Personnel will follow the facility's safety requirements to prevent fires in other areas.

### Dust

In areas where process dust might cause eye and/or respiratory problems, all sampling personnel will wear dust masks and sealed goggles, as necessary.

### 4.10.4.2 Chemical Hazard Abatement

*{tc "11.4.2 Chemical Hazard Abatement " \l 3}*

#### Personal Protective Equipment

All on-site test team personnel will, at a minimum, wear:

- Hardhat;
- Safety glasses;
- Safety shoes or boots; and
- Work clothing (long-sleeved shirts), if required.

Beyond the personal protective equipment routinely required as listed above, the personnel on the following tasks will wear additional gear as specified below.

### Source Samplers

Under general sampling conditions, there is an opportunity for exposure to contaminants transported in the flue gases. Therefore, during set-up, breakdown, or under any other conditions where exposure may result, personnel wear full-face respirators with organic vapor/HEPA filter cartridges.

### Work Practices

Compressed gases will be used during the sampling and analysis phase of this program. No protective equipment is required, but care will be exercised when handling, shipping, connecting and disconnecting gas lines to the cylinders.

## 5.0 TEST EQUIPMENT SPECIFICATIONS

### 5.1 Objective

The objective of this section is to identify and describe the principal test equipment for use in the Phase II program and justifies decisions to use particular devices with regard to accuracy and robustness.

### 5.2 Equipment

#### 5.2.1 Gaseous Emissions Measurement

Measurement of oxygen will be made using a paramagnetic analyzer as described below. All other gaseous exhaust emissions constituents will be measured using an FTIR analyzer as configured by Spectral Insights.

##### 5.2.1.1 Oxygen Analyzer

The oxygen analyzer will be a California Analytical Model 100P, which measures the paramagnetic susceptibility of the sample gas by means of a magneto-dynamic type measuring cell. The measuring cell consists of a dumbbell of diamagnetic material, which is temperature controlled electronically at 50° C. The higher the oxygen concentration, the greater the dumbbell is deflected from its rest position. This deflection is detected by an optical system connected to an amplifier. Surrounding the dumbbell is a coil of wire. A current is passed through this coil to return the dumbbell to its original position. The current applied is linearly proportional to the percent oxygen concentration in the sample gas. This concentration is displayed on a digital panel meter.

The 100P is a rack-mounted paramagnetic analyzer that provides two types of analog outputs: (1) Current (0-20 or 4-20 mA) or (2) Voltage (0-1 or 0-10 volts). The 100P requires a conditioned sample. Sample conditioning is achieved with a gas chiller (Apex Instruments).

The analyzer 4-20 mA output is fed to a 16-bit ADC system (Strawberry Tree) for storage and display. Data is collected every 2 seconds and averaged for typically 1 minute. Digital filtering algorithms (by Spectral Insights) are used to process data.

**Table 5.1**  
**O<sub>2</sub> Analyzer Specifications**

| Parameter                  | Value                   |
|----------------------------|-------------------------|
| Concentration Ranges       | 0-5, 0-10, 0-25 percent |
| Response Time (90 percent) | 2 seconds               |
| Linearity                  | Better than 1 percent   |

##### 5.2.1.2 FTIR Analyzer

The Spectrometer to be utilized is a Thermo-Nicolet model Nexus 670. This is Thermo-Nicolet's research-grade, fully upgradeable FTIR spectrometer. The instrument is fitted with a 1 to 10 meter optical path length heated cell made by Infrared Analysis (Model 4-10) with custom

coupling optics by Spectral Insights. This cell allows the FTIR spectrometer to measure gas samples with sub-ppm sensitivity for many species.

Data collection is controlled by custom software (by Spectral Insights) that interfaces with the Thermo Nicolet OMNIC software. The custom software contains digital signal processing algorithms, which enable lower detection limits for some species.

**Table 5.2**  
**FTIR Specifications**

| Parameter                    | Value  |
|------------------------------|--|
| Spectral Range               | 400 to 4000 wave numbers                                       |
| Resolution                   | 0.5 wave number  |
| Data collection rate         | 1 spectrum per 1.2 seconds                                     |
| Gas Cell Optical path length | 3.2 meters   |
| Number of Compounds Measured | 10 or more, depending on application                           |
| Noise Equivalent Absorbance  | $1 \times 10^{-5}$ (5 minute average) @ $2000 \text{ cm}^{-1}$ |

### **5.2.2 Particulate Sampling**

Two different types of partial dilution tunnel, particulate sampling systems were evaluated. The first was the SPC model 472 Smart Sampler manufactured by AVL. The second was the BG-2 system as manufactured by Sierra Instruments based on dilution tunnel technology licensed from the Caterpillar Engine Company. (See Appendices A, B, C, and D.)

Both systems offer (relative) portability and high accuracy. Final decision regarding which system to use will be based on pricing and availability at the time of testing.

#### **5.2.2.1 AVL SPC 472 Smart Sampler**

The AVL system offers excellent accuracy and the company has demonstrated extensive application experience with shipboard particulates testing in Europe. This model represents the third generation in the product's development, indicating a mature device. Meetings with representatives from AVL to discuss the current project at the March 2002 Society of Automotive Engineers conference confirmed the suitability for their device for the bus and ferry testing.

The complete system includes sample probe, dilution tunnel, filters, pumps, flow meters and a data acquisition system for real-time data logging.

#### **5.2.2.2 Sierra Instruments Model BG-2**

Sierra Instruments Inc. combined their expertise in the manufacture of precision flow meters with Caterpillar's micro-dilution tunnel design to create the BG-1/2 family of micro-dilution tunnel test devices. Similar to the AVL Smart Sampler, the BG-2 is a complete, modular engine test station including sampling equipment, the dilution pumps, flow meters, controls and a data acquisition program written in National Instruments Labview software. (Refer to Appendices E and F.)

### **5.2.3 Air Flow**

Due to the relatively small engine sizes concerned in the test program, and based on the requirement to obtain best possible accuracy, it was decided to utilize direct measurement of the inlet air flow in order to determine exhaust flow rate and ultimately mass emissions rates.

Based on a survey of the technical literature, including other marine engine test work performed by the USCG and MARAD, AETC selected the model 780S-EIA, Engine Inlet Airflow meter manufactured by Sierra Instruments was selected for this task (Appendices G and H).

This device is a direct indicating mass flow meter incorporated into an airflow conditioning body. The flow conditioner allows the meter to function accurately even in short runs of piping. Since it is a direct (thermal method) flow device, pressure and temperature corrections are not necessary.

For testing, the output signal from the transmitter will be connected to the data acquisition computer.

### **5.2.4 Fuel Flow**

Fuel flow will be measured on the supply and return lines of each test engine utilizing precision, positive displacement meters manufactured by KRAL (Appendix N). Net fuel consumption (pounds) will be summed with the inlet air mass flow to determine exhaust flow. The wide range flows coupled with excellent accuracy will permit the use of the same meter pair for both the ferry engine and the bus engine.

The meters will be the KRAL Volumeter model OMG in conjunction with KRAL's BEM 4U flow management and totalizing unit.

### **5.2.5 Shaft Torque**

Shaft torque will be measured on the Ferry to monitor engine power output. A reusable / removable strain gage collar system will be utilized. An analogue voltage output from the torque measuring signal conditioning unit will be brought into the data acquisition system. The system selected is the Wireless Data Corporation model 1625 (Appendix O). Due to the use of strain gages attached to parallel bars, the accuracy of the system exceeds that of shunt calibrated strain gages mounted directly to the drive shaft.

The system can also be moved to different shafts in order to compare the horsepower developed by each of the four different propulsion engines on the ferry.

### **5.2.6 Engine Communications**

Communication with the engines will be necessary for both tests, however, in the case of the bus, obtaining the duty cycle information will be of paramount importance to the representativeness of the emissions data.

Both engine types utilize an electronic governor and engine control module which can communicate, via a serial port or USB connection, to a laptop computer operating companion software.

#### 5.2.6.1 Detroit Diesel DDEC

Of the two products, the DDEC system and software is vastly more capable, benefiting from years of development and use by the engine manufacturer. The DDEC system will be to obtain accurate duty cycle load profiles for the bus while riding the bus for approximately one-week of commuting.

The software permits monitoring and logging of all engine parameters for which a sensor is installed including all non-emissions engine parameters needed for the testing.

DDEC technical literature, including a list of diagnostic fault codes provides a clear summary of the amount and type of data available with the system and is presented in Appendices K and L.

#### 5.2.6.2 Cummins INSITE

The Cummins software, “INSITE” is much simpler than that offered by Detroit Diesel, however, it will provide the basic engine data required including torque, fuel pump pressure and engine speed. (Refer to Appendix N.)

## 6.0 PHASE II SCHEDULE AND COST ESTIMATE

### 6.1 Objective

The objective of this section is to assess the effort required to plan, prepare, conduct and complete all activities necessary to accomplish comprehensive engine and exhaust emission pollutant characterization testing for a the passenger ferry and transit bus.

### 6.2 Summary of Phase II Scope of Work

The effort required to plan, prepare, conduct and complete all activities necessary to accomplish comprehensive engine and exhaust emission pollutant characterization testing for a transit ferry and bus is summarized below on a task-by-task basis.

**Task IA - Pre-Test Design and Preparatory Work:** This task will consist of the detailed design work that must be completed prior to mobilization of the test team. This effort includes such activities as design and fabrication of sampling ports, determination of inlet air system modifications required for the installation of combustion airflow metering equipment, design and fabrication of brackets and piping modifications for fuel oil supply and return meters, etc.

**Task IB - Automotive Emissions Data Survey:** Work on this task includes the review and analysis of existing emissions data for the purpose of developing comparable parameters for automobiles in the same commute service as the bus and ferry.

**Task II - Bus Pre-Test Data Collection:** To develop a representative transit bus passenger load profile, a Seaworthy project team technician will ride the bus for one week, equipped with a laptop computer connected to the on-board engine control system. At completion of the week of data collection, the technician and an engineer will review the data and determine the final load profile to be utilized for bus emissions factor computation.

**Task III - Emissions Testing of Bus:** This task will address controlled emissions test of the bus engine while in operation on the chassis dynamometer.

**Task IV - Ferry Pre-Test Set-up:** All work necessary for preparing the ferry for the emissions testing, including the installation of the fuel oil and air flow meters, installation of the shaft torque meter and installation of sampling probe penetrations into the exhaust system will be completed as part of this task. In addition, all required test equipment will be brought aboard. Test equipment checkout and initial calibration will also be performed at this time.

**Task V - Emissions Testing of Ferry:** Emissions testing of the ferry engine will consist of obtaining specific emissions data for a typical round trip. Up to three (3) emissions reduction methodologies will also be tested, including alternative diesel fuels (bio-diesel and/or fuel water emulsions).

**Task VI - Summary Report:** After thoroughly and precisely reducing and analyzing all collected emissions and related data to engineering units, the Seaworthy team will prepare a detailed summary report. Appendices of the report will include all raw data and instrumentation calibration information. The report will describe the test methods utilized, present an analysis of



the errors (if any) for all measurements taken, discuss the test results and make recommendations for future follow-on test work, if necessary. In addition, the efficacy of any emissions reduction methodologies tested aboard the ferry will also be addressed.

### **6.3 Phase II Schedule**

For the in-situ testing portion of the Phase II effort, as shown in Figure 3-1, the total elapsed time is approximately 60 days. It is anticipated that an additional 60 days will be added to the proposed transit bus and ferry engine emissions test period to address all the other administrative and contractual program requirements; to provide some margin in the schedule in case of unforeseen delays in obtaining test equipment or consumables; and to address any slippage in the availability of the transit bus or ferry for testing.

### **6.4 Phase II Cost Estimate**

Table 4.1 presents a categorized breakdown of anticipated costs to accomplish the in-situ transit bus and ferry engine emissions testing work scope outlined previously.

**Table 6.1**  
**Phase II Cost Estimate**

|  |                  |
|--|------------------|
| 1. Labor (SSI, AETC, Spectral Insights)  | \$ 127,710       |
| 2. Test Equipment (F.O. meters, torsion meter, air flow meters, dynamometer and dilution tunnel, rental, etc.) | \$ 29,770        |
| 3. Other Project Related Costs (fuel oil, laboratory materials, travel/equipment, transportation, etc.)        | <u>\$ 47,200</u> |
| <b>Total:</b>  | <b>\$204,680</b> |

It should also be noted that the above, more precise Phase II cost estimate is approximately 12% higher than the original estimate submitted with our Phase II proposal to CCDoTT in November 2001. This difference is due to increases in fuel and laboratory materials and related consumable costs that more than offset the lower total labor cost shown above when compared to our initial labor cost estimate as proposed in November 2001. The costs shown above are also based on the assumption that all testing will be completed during the first quarter of Fiscal Year 2003.

## 6.5 Inventory of Harmful Emissions and Regulations

Each category of harmful exhaust emissions represents unique threats to health and the environment. However, one of the problematic issues in restoring air quality is that proven methods of reducing one harmful component of engine exhaust can often increase the emission of another. As one example, tests conducted to date on biodiesel fuel indicate that it reduces harmful particulate emissions, but increases equally damaging emissions of NO<sub>x</sub>. The inventory of harmful diesel engine exhaust emissions to be reduced and the threat(s) each imposes can be briefly described in roughly descending order of importance as follows:

1. *Oxides of Nitrogen (NO<sub>x</sub>)* have local, regional, and global effects. They cause climate change, atmospheric acidification, increased ground level ozone (and consequent respiratory diseases), and formation of toxic compounds. In addition, NO<sub>x</sub> compounds have been identified as precursors to toxic particulate. The California Air Resources Board estimates that heavy duty mobile engine sources generate 40 percent of NO<sub>x</sub> emissions statewide, chiefly from trucks, aircraft, locomotives, and marine vessels.
2. *Particulates, or Particulate Matter (PM)* have local effects. They are characterized as solid particles primarily less than 2.5 microns in diameter. PM contributes to smog, reduces atmospheric visibility and is a pulmonary carcinogenic. When inhaled and lodged in the lung, PM can cause cancer. Particulate also collects on and discolors buildings, monuments, bridges, and other structures.
3. *Oxides of Sulfur (SO<sub>x</sub>)* have both local and regional effects. They cause atmospheric acidification and form toxic compounds, which precipitate out into lakes, streams and reservoirs as acid rain.
4. *Carbon Dioxide (CO<sub>2</sub>)* has a global effect. It is a leading greenhouse gas, believed to contribute to trends of global warming.
5. *Hydrocarbons (HC)* have local and regional effects. They contribute to ground level ozone and consequent respiratory disease.
6. *Carbon Monoxide (CO)* has a local effect. It is toxic to breathe.

Until the 1980's, engine manufacturers concentrated development efforts on continuously improving fuel economy, reliability, power-to-weight ratio, durability, life cycle economy, and overall performance. Little attention was paid to exhaust emissions because they were not a legally recognized problem. Although emissions were largely ignored during this period of advancement in engine thermal efficiency, reduced emissions was a fortunate, but unintended consequence. The improved fuel economy that diesel engines would achieve has brought a significantly beneficial change to global air quality. Because diesels burn the least fuel per unit of power output, diesel engine exhaust contains much lower quantities of toxic and global warming CO and CO<sub>2</sub> per unit of power output than any other type of internal combustion engine. In short, because of fundamental differences in fuel consumption, a modern automotive spark ignition engine or gas turbine will tend to burn more fuel and emit from 10 to 30 percent more CO and CO<sub>2</sub> than a comparable diesel engine developing the same power.

As scientific knowledge of air quality problems increased, the need to legally regulate engine emissions became apparent. The nationwide fleet of automotive (spark ignition) engines was

quickly recognized to have the most numerous point sources of air pollution. These engines were the first to face regulation, fuel (gasoline) reformulation, and design improvements to reduce harmful emissions. Exhaust catalysts became standard equipment and computer-controlled fuel injection systems superseded the mechanical carburetor, enabling substantial improvements in automotive exhaust emissions. The reformulation of gasoline and steady retirement of older automobiles, combined with the required exhaust gas catalytic converter caused a significant improvement in vehicular emissions by the end of the twentieth century.

The second most numerous category of mobile equipment to be regulated was the diesel-powered highway vehicle. The first effort in the U.S. to improve and reduce highway diesel engine emissions was the introduction of low-sulfur highway diesel fuel in 1993. Subsequent engine design improvements such as electronic fuel injection and exhaust gas recirculation began to appear on new highway vehicle engines, further improving the emissions profile. A major stumbling block on the road to capital improvements of the nation's trucking fleet has been the inherent robustness of diesel-powered trucks and buses on the roadways. Truck and bus drive trains are significantly costlier than automobiles and are designed for decades of reliable service. The greater durability and cost of these engines makes for slow retirement of generations of vehicles, which are pollution sources. The automobile fleet, on the other hand, with its short life span is quickly updated and replaced with more efficient, cleaner-burning engines. Nevertheless, new highway diesel engines have been developed and are now available with emission characteristics that are 40 percent less polluting than earlier models.

The most recent category of mobile source emissions to be regulated is the off-road diesel engine. These comprise the diverse inventory of railroad locomotive, mining, earth moving, heavy construction equipment, marine container terminal equipment, general seaport cargo handling equipment, and ship engines. Engines in these categories, while comparatively few in number and often subject to lower duty cycles than their highway counterparts, are now the focus of increased regulatory scrutiny. The timing and scope of anticipated international regulations on marine engine emissions is still being debated. The Montreal Protocol of 1987, amended in London in 1990, and the Kyoto Protocol of 1997 have largely framed the debate. International Maritime Organization (IMO) MARPOL (marine pollution) regulations are effectively motivating engine manufacturers and U. S. government regulatory agencies towards lower engine emissions. MARPOL 73/78 Annex VI Marine Diesel Engine Requirements sets worldwide limits on engine NO<sub>x</sub> and SO<sub>x</sub> emissions.

U.S. federal and state agencies are simultaneously focusing more on the adverse impacts to air quality by marine diesel engines and are working to improve emission standards. In 1998, the U.S. Environmental Protection Agency proposed a set of emission standards for all diesel engines rated from 50 to 750 horsepower. In 1999 the E.P.A. published NO<sub>x</sub>, HC, CO, and PM emission standards for commercial marine engines rated greater than 50 horsepower. These standards are scheduled to be effective in 2004, 2005, and 2007, depending on engine cylinder displacement. Engine manufacturers expect to meet these standards with new production designs. Meanwhile, the inventory of existing marine engines with more harmful emissions characteristics continues to constitute a serious air quality problem. The two pollutants believed to require the most rapid reduction are NO<sub>x</sub> and PM.

## **7.0 EMISSION REDUCTION TECHNOLOGY EVALUATION**

### **7.1 Objective**

The objective of this section is to review and analyze engine emission-reduction technologies that are best suited for incorporation in diesel engines and systems for use in passenger ferry applications.

### **7.2 Scope of Engines and Fuels Addressed**

#### **7.2.1 *Recreational Boating***

With few exceptions, recreational watercraft are powered either by diesel- or gasoline-powered (spark ignition) engines. While prominent in recreational boating, gasoline fueled engines are virtually nonexistent within industrial marine applications. To date, excepting two-cycle outboard motors and engines on personal watercraft, recreational marine engines have been subjected to virtually no significant emission regulations. No recreational boating engines are included in the scope of this program element.

#### **7.2.2 *Deep Sea Vessels***

Diesel engines are the vastly dominant source of propulsion and auxiliary power aboard large oceangoing ships. The rare exceptions to this rule comprise either nuclear or oil/coal-fired Rankine steam-cycle plants, and gas turbine plants, or one of the above in the case of a liquefied natural gas (LNG) tanker, burning cargo boil-off for fuel. This program element does not address the emissions of any large seagoing ships. Deep-sea ships almost invariably operate on a variety of high-viscosity, heavy residual-fuel oils, which are outside the scope of this analysis.

#### **7.2.3 *Inland Waterway and Harbor Craft***

The remaining classes of vessels are diesel-powered inland waterway and harbor craft. This class of vessels operates on a much more restricted, typically more refined, range of fuels. This report addresses emissions from the passenger ferry, one segment among the inland waterway and harbor craft class of vessels. Power outputs for the typical high-speed diesel engines utilized in main propulsion and auxiliary engine applications in these vessels range from 150 to 3,000 brake horsepower (BHP). Passenger ferry engines have been designed to operate on distillate liquid fuel termed marine gas oil (MGO), the marine equivalent of standard California highway diesel fuel known as Number 2 diesel oil.

The standard California highway diesel oil is low-sulfur diesel fuel. MGO was once differentiated from low-sulfur highway diesel fuel by statutory limits that maintained a lower sulfur threshold for highway diesel fuel than for MGO. Low-sulfur highway diesel fuel was set apart from dirtier (MGO) fuels by use of a red-colored dye additive. Eventually, for economic and logistical reasons, MGO was folded into the much larger highway fuels market. Consequently, there is no difference between the fuels today, and MGO, too, is low-sulfur and dyed red. The diesel-powered ferry engines analyzed for this program will burn low-sulfur highway diesel fuel, the same as the bus engines burn, because that is the actual fuel used by each of these transit operations.

### **7.3 Marine Diesel Engine Emission Reduction Alternatives**

A broad range of alternatives exists to reduce harmful marine engine emissions.

Environmental advocates have endorsed most of these options at one time or another. The challenge posed by many technologies is that they are either too costly or are inconsistent with the safety, regulatory, and operational requirements of practical operating vessels. Many green concepts themselves are obstacles to plausible implementation such as solar-powered storage batteries, stored kinetic energy flywheels, the inconsistency of wind-power, the high cost, and the massive size-to-power ratios that many alternative prime movers offer, even in their best configurations. Many alternative, and presumably cleaner-burning marine fuels that have been promoted for ferry use, such as biodiesel and compressed or liquid natural gas, are likewise problematic for their high costs, safety, logistics, and other operating issues (such as the refitting of fueling, storage and engine systems for natural gas fuel). Some alternative fuel problems will be resolved in the future. In the near term, cost and technical obstacles are preventing a broader switch to alternative fuels in existing vessels.

The forecast for other advanced engineering concepts, in particular fuel cells, is likewise beyond immediate reach. The current and ten-year anticipated levels of development in fuel cell technology and comparably advanced energy sources (such as nuclear power) preclude their near term application to all but a few experimental vessels as restricted by fundamental laws of economics, physics, chemistry, and thermodynamics.

There are, however, practical alternative solutions available to reduce marine diesel engine emissions in the near term. These can be categorized under three general categories: feasible alternative fuels, replacement of older engines, and engine system modifications. A primary benefit of any practical cleaner-burning fuel is that its impact is immediate and universal, regardless of engine type or age. Whether or not engine replacement or modification may be economically practical, a successful fuel change is capable of delivering the most wide-ranging benefits and therefore should be considered a primary step to achieve lower diesel engine exhaust emissions.

#### **7.3.1 Low Sulfur Fuels**

One of the first breakthroughs in diesel engine emission reductions was the U.S. introduction of the low-sulfur highway diesel fuel in 1993. Prior to this reformulation, the sulfur content of No. 2 diesel oil was approximately 5,000 parts per million (ppm) or roughly 0.5 percent. Low sulfur highway diesel fuel limits sulfur content to 2 percent of this number, or a maximum of 100 ppm. The use of low sulfur highway fuel, as mandated by Clean Air statutes, led to significant benefits for regional air quality, described below.

- (1.) Engine emissions of acid rain-causing SO<sub>x</sub> were reduced 98 percent. SO<sub>x</sub> emissions occur commensurately with sulfur content of the fuel oil.
- (2.) A less-noticed achievement was the small increases in engine performance per unit of fuel consumed. The drop in sulfur content increased the mole fraction of hydrocarbons in the fuel, which account for the superior properties of flame propagation and heat content in fuel oils. The total energy released from combustion of low sulfur fuel is therefore slightly greater than with pre-1993 No. 2 diesel fuel.

- (3.) Engine wear dropped as much as 50 percent. Cleaner, sulfur-free combustion yielded lower engine wear and subsequent repair and maintenance costs. Much of the wear improvement is attributed to the absence of acidity that sulfur is known to form in the engine lubricating oil.
- (4.) Another direct result of the cleaner combustion process was a small but measurable decline in toxic exhaust particulate matter (PM).

These improvements to air and equipment came with a temporary cost. The initial price of low-sulfur highway diesel fuel was approximately 5 percent greater than its higher-sulfur alternative. Once the oil refiners recouped their investment for the low-sulfur conversion, and as production and distribution of the new fuel matured, the early cost premium quickly disappeared. A second notable problem occurred with some of the older engines, as they sustained compatibility problems with some of the older-type rubber gaskets and seals. This problem, though predictable and readily corrected, is useful for future iterations of fuel reformulation. Engine owners and operators must first contact the original equipment manufacturer to verify that all propulsion components will function with new fuel or other emissions-control devices. By 2006, industry is likely to use even lower sulfur fuel – 15 ppm vice today's "low sulfur" fuel of 100 ppm – as required by pending EPA regulations.

### **7.3.2 *Emulsified Diesel Fuels***

Consideration of water emulsions in diesel fuel should first stipulate a low or ultra-low sulfur diesel fuel for the benefits discussed above.

The emissions improvement achieved by properly engineered fuel-water emulsification is universal and immediate, regardless of engine age or make. The primary benefit of water-fuel emulsions in diesel engines is a well-documented reduction in NO<sub>x</sub> emissions. NO<sub>x</sub> can roughly be lowered one percent for each percent (by weight) of water content in the fuel, up to a practical limit of 25 to 30 percent, depending on engine design and service profile. In cases of the largest-bore marine diesel engines, emulsions with up to 50 percent water content have been successfully used. This reduction is achieved by lowering the peak combustion temperature in the engine cylinders. NO<sub>x</sub> production is a cubic function of combustion temperature. Better fuel atomization and more complete combustion serve to offset any reduced thermal efficiency resulting from the quenching effect of water during the combustion process. The net impact on engine power development and fuel economy is minimal.

It is important to recognize that water contains no energy and, to the extent that water displaces fuel in the emulsion, the total volumetric flow of an emulsion will exceed the flow of unblended (pure) diesel fuel required to produce the same power. This means that it may be necessary to resize (enlarge) engine fuel system components, in particular injector port size, and water-storage tanks, to handle the increased volume of the emulsified fuel blend.

Vessel owners and operators have been reluctant to implement emulsified fuels because most engine manufacturers have been unwilling to extend warranties to cover engine operation on emulsified fuels. In large part, OEMs have felt no compulsion to include emulsions-operation under engine warranty when the propulsion market has overwhelmingly abided pure, unblended diesel fuel and its attendant higher emissions as acceptable. The engine warranty limitation has

been a simple matter of practical self-interest for OEMs. The pure-diesel-only paradigm must be overcome if emulsified fuel systems are ever going to take their deserved place in engine emissions-reduction technology. The gradual growth in successful land-based emulsified fuel applications indicates that emulsions are finally trending toward greater industrial acceptance and use.

There are two fundamental approaches to utilizing water-fuel emulsions, described below.

#### 7.3.2.1 Onboard Emulsification Systems

This approach requires design and installation of a suitably sized fresh water storage tank, a piping system, an electric motor-driven fuel blender/agitator, an emulsifying surfactant chemical for use in low sulfur diesel fuels with water, and a control system to regulate fresh water flow into the blend. The blending control system must achieve minimum NO<sub>x</sub> emissions under variable operating conditions. Considerations for this system must address the initial capital investment, ongoing (but minimal) system energy consumption, system maintenance and repair costs (also very small), and availability of fresh water supply when refueling.

There are several advantages to onboard emulsification systems vice the loading of pre-blended emulsion fuels. Advantages of onboard blending include a vessel life-cycle savings in fuel costs, freedom from complications which might arise with the stability of pre-blended fuels during long-term storage, such as during vessel inactivation; roughly 25 percent higher fuel quantities per delivery, greater options for selecting fuel vendors, and the ability to blend fuel emulsions tailored for individual engine applications.

#### 7.3.2.2 Preblended Emulsified Fuels

As the name implies this approach utilizes direct delivery of emulsified fuel to the vessel by tank truck. The blending is accomplished at a remote facility and the water-fuel emulsion is simply pumped into the vessel's fuel storage tanks for use. The Lubrizol Corporation, for example, has developed a proprietary blend of emulsified fuel called PuriNO<sub>x</sub>. PuriNO<sub>x</sub> contains a patented stabilizing additive to maintain the emulsion over prolonged periods of time.

There are several advantages of pre-blended fuel emulsions. The vessel owner/operator has no initial capital investment, nor an extra onboard (fuel) system to operate, maintain and repair, nor a need to acquire and store volumes of fresh water.

The disadvantages are slightly higher life-cycle costs for fuel, the potential for instability of the emulsion during extended storage periods, less flexibility in selecting the ratio of the fuel-water blend, restricted sources of fuel vendors, and roughly a 25 percent reduction in the volume of fuel (due to its displacement by water). The displacement issue equates to larger fuel tanks or more frequent refueling events.

#### **7.3.3 Summary**

Operators of diesel-powered vessels can lower their fleet exhaust NO<sub>x</sub> emissions by as much as 25 to 30 percent for smaller-bore diesel engines and as much as 50 percent for the largest-bore diesel engines, by employing water-fuel emulsion technology. The first priority for bringing proven fuel-water emulsion technology to broader commercial application is to overcome the

existing proprietary, often parochial, resistance by many engine manufacturers to the acceptance of this innovation. Manufacturers' acceptance of emulsions is the critical step toward commercial application, which in many cases awaits the extension of warranties to cover engines using this technology.

The selection of onboard emulsion blending or bunkering with pre-emulsified fuel depends on several factors. In the case of pre-blended emulsion fuels, principal considerations include the availability of multiple suppliers of emulsion fuels for price competition; whether more frequent refueling is acceptable, or if the vessel's fuel tanks may be expanded to accommodate a greater volume of less energy-dense emulsion fuel to maintain the same range as operation on pure diesel oil. In the case of onboard blending of emulsion fuels, principal considerations include whether there is such limited availability of pre-blended fuel vendors that prices remain artificially high, whether the capital cost of the water and surfactant tanks and blending systems is manageable, and whether there is space enough aboard the vessel to outfit it with that equipment. A simple list of pros and cons for each method, with respect to a particular vessel and operating location, would point to the better option.

#### **7.4 Engine Replacement for Reduced Emissions**

Diesel engine designs have evolved substantially since the 1980s to attain significantly cleaner exhaust emissions. Older marine engines, particularly two-cycle models, cannot approach the 40 percent lower NO<sub>x</sub> emissions typically achieved by modern four-cycle engines equipped with electronic fuel injection systems. Other notable design improvements to the diesel engine, such as exhaust gas recirculation, are continually added to new generations of engines. Each successive generation of engines, complete with new developments in emissions control, achieves lower levels of harmful NO<sub>x</sub>, HC, and PM emissions.

It follows that every owner/operator of a vessel with a technically obsolete propulsion engine, from an emissions standpoint, should consider the option of replacing that engine with the newest equivalent low-emissions model. The basic obstacle to this solution is the inherently high cost of replacing a durable marine diesel engine. The vast majority of older units are too reliable, economical, and serviceable to be discarded lightly. Vessel life cycle economics bear heavily on the engine replacement decision and are seldom favorable without substantive public assistance. A variety of government incentive programs exist to reduce the financial burden on vessel owners and operators wishing to develop cleaner fleets. The State of California's Carl Moyer Memorial Program is an example of a program that has effectively promoted the replacement of environmentally obsolete engines with cleaner, modern substitutes. The Carl Moyer Memorial Program received \$114,000,000 in appropriations between 1998 and 2002 and has facilitated enormous near-term emissions benefits that California must achieve in order to meet impending federal air quality deadlines. Shrewd vessel owner/operators will investigate the availability of incentive programs that apply to them by contacting the relevant air quality agencies to get the specifics of how to participate in such programs. In many cases, plans to lay up a vessel for extensive repairs, re-powering, or other life-extending modifications will coincide nicely with an emissions-reducing engine replacement program.



## **7.5 Engine System Modifications for Reduced Emissions**

There are several proven propulsion plant modifications for reducing harmful engine exhaust emissions. These modifications can include humidification of the engine intake air, altered fuel injection and valve timing, ceramic coatings on valves and piston crowns, or post-combustion treatment of exhaust gases. Some of these approaches are readily applicable to marine installations and others, for unique reasons, are not. The available options span a measurable range of cost-effectiveness. Merits of each technique should be evaluated on a case by case basis. The emphasis on near term and future marine air-quality problems will be placed on NO<sub>x</sub> and PM<sub>10</sub> emissions. In the sections that follow, the four most promising retrofit options for limiting NO<sub>x</sub> and PM will be described and their merits and drawbacks assessed.

### **7.5.1 Selective Catalytic Reduction (SCR)**

The maximum reductions in NO<sub>x</sub> emissions effected to date have employed selective catalytic reduction technology. An engine exhaust system fitted with an SCR module will typically reduce NO<sub>x</sub> emissions by 75 to 90 percent, depending on engine design and service profile. This is far in excess of what can be achieved with simple water-fuel emulsions. In addition, SCR applications on diesel engines have demonstrated up to an 80 percent reduction in unburned hydrocarbons (HC) and a 20 to 50 percent reduction in particulate (PM). The Europeans have proactively and fairly successfully applied SCR technology to diesel engines. In the United States, the application of SCR is now gaining momentum.

SCR modules require minimum exhaust gas temperatures that are generally not achieved at loads less than 30 percent of an engine's rated capacity. SCR is therefore effective in reducing emissions only at sustained engine loads in excess of 30 percent. SCR applications in the marine industry have been very rare to date. Impediments to broader acceptance of SCR in marine transportation are outlined below.

- Sulfur content in fuel is incompatible with SCR. The previous dominance of (high sulfur) marine gas oil and heavy (residual) fuel oil as standard marine engine fuels prohibited use of this technology. The specification and exclusive use of low sulfur and ultra low sulfur distillate fuels will overcome this industry impediment.
- The acquisition cost of marine SCR equipment remains high. At present, each new SCR installation is virtually custom designed and built to suit a specific application. There is no "mass production" of SCR equipment for heavy-duty diesel engines. As a result, economies of scale have not emerged in marine or industrial SCR purchases to date. SCR installation costs on smaller highway truck and bus engines have ranged from \$10,000 to \$50,000 per unit. Larger marine engines will face significantly higher costs. A recent (February, 2002) cost estimate for a European SCR/particulate filter installation on a 7,000 horsepower diesel ferry was \$500,000. At least one vendor, RJM Corporation, has progressed in the situation by offering pre-engineered designs that employ standardized components suitable for engines from 100 to 3,000 horsepower.
- The close confines of typical marine engine room spaces, particularly aboard workboats and high-speed passenger ferry vessels, generally do not allow the space required for SCR modules and urea storage tanks.

- The additional weight of an SCR installation can also present a significant problem for finely tuned high-speed passenger vessel designs. With an SCR module aboard, the passenger capacity (payload) may be diminished to maintain vessel displacement tonnage and service speed.
- SCR requires continuous injection of a reagent into the exhaust gas flow. The optimum choice for this application is urea, which is a naturally occurring non-hazardous material. Nevertheless, the need to continuously supply any reagent requires addition of a storage tank and a delivery piping system, and some degree of operator-attention to ensure that flow is maintained and that ample supplies of reagent are on hand. The cost of the reagent itself may be modest (5 to 8 kilograms are used per megawatt-hour) remains a consideration.

Despite some significant obstacles, SCR technology still embodies the maximum opportunity for practical reductions in NO<sub>x</sub>, HC, and, to a lesser extent, PM emissions from existing marine diesel engines. The capital expense of SCR can be entirely absorbed by the vessel owner or shared by a variety of government-sponsored air quality-improvement incentive programs. If a vessel can accommodate the space and weight penalties of SCR equipment, then this technology merits serious consideration.

### **7.5.2 Exhaust Gas Recirculation (EGR)**

Exhaust gas recirculation (EGR) is a development in diesel engine control technology which obtains significant NO<sub>x</sub> reductions. The recirculation of exhaust gas reduces peak temperatures in the combustion chamber (engine cylinders) by slowing the reaction rates and absorbing some of the heat generated from combustion. While NO<sub>x</sub> is reduced, PM and fuel consumption can increase, especially at high loads, because available oxygen for combustion is reduced and burn times are consequently lengthened. Reducing the flow of recirculated exhaust gas or by cooling the exhaust gas, and reducing its specific volume, can enable better combustion and mitigate these penalties at high load.

In the case of large slow-speed marine diesel engine, EGR in conjunction with direct water-injection (a variant of the emulsion technology), a 70 percent reduction in NO<sub>x</sub> was achieved. Without EGR, only a 50 percent NO<sub>x</sub> reduction was achieved. Also with some large, slow-speed marine diesel engines, the exhaust was recirculated simply by decreasing the efficiency of the scavenging process and trapping additional exhaust in the cylinder. This internal EGR eliminates the need for external hardware such as piping and valves, reducing cost and complexity. Second, by capturing the exhaust gas in the cylinder and not recirculating it into the intake system, deposits and wear are eliminated from the intake manifold and turbocharger that might otherwise be caused by EGR. The cost of retrofitting an EGR system to the average truck or bus engine is estimated to be \$13,000 to \$15,000. The cost is expected to be higher for a larger marine diesel engine.

### **7.5.3 Particulate Filters**

This particular option could achieve only near-term practicality in a minority of marine engine applications, specifically on low powered vessels. The sole reason that particulate filters are worthy of discussion is that they are the most effective established means to reduce PM emissions by much as 90 percent. As mentioned above, the use of low and ultra-low sulfur

diesel fuels, water-fuel emulsions, modern low-emission engine designs, and SCR all have beneficial impacts on particulate emissions. The sum of these initiatives, while not directly additive, would probably enable a cumulative reduction of PM emissions by roughly 20 to 55 percent, depending on engine model, age, and operating profile. By contrast, the particulate filters cut PM emissions 90 percent, regardless of engine model, age, and operating profile. It is therefore anticipated that more government incentives will promote the installation of particulate filters, as attention focuses on the carcinogenic effects of PM.

Until now, particulate filters have primarily been demonstrated in thousands of European stationary, mining, and highway vehicle applications. Typical vehicular PM filter costs are in the range of \$7,500 each. A marine unit, even for a small ferry vessel, would likely be considerably more expensive. Periodic maintenance (filter regeneration/cleaning) requirements would also add financial burdens to the vessel owner. For large, high-speed vessels, these practical and economic issues would likely preclude particulate filters from consideration until less troublesome filter technology were demonstrated. The list of other prerequisites and problems for particulate filters generally follows the pattern already established for emissions reducing options discussed above.

- Low sulfur fuel is required.
- Vessel engine room space and weight limitations may preclude consideration.
- Particulate filters will increase backpressure on engine exhaust flow. Excessive backpressure compromises fuel economy and, therefore increases emissions of carbon-based greenhouse gases.

In summary, it is clear that the benefits of particulate filters have been well established, but that too many penalties come with this technology, as it exists today, for widespread acceptance by the marine industry. The optimum installation would undoubtedly be on a new vessel designed from the beginning to incorporate both SCR and a particulate filter. Nevertheless if, as expected, future air quality regulations impose stringent restrictions on particulate emissions, some form of particulate filter could have to be considered.

#### **7.5.4 Diesel Oxidation Catalyst**

The diesel oxidation catalyst is a stainless steel canister with a honeycomb structured catalyst support, fixed into the exhaust stream. The platinum or palladium metal catalyst coatings inside convert exhaust gas pollutants to less harmful gases by a process of chemical oxidation. The catalyst is most effective at converting carbon monoxide (CO) and unburned hydrocarbons (HC) into CO<sub>2</sub> and H<sub>2</sub>O vapor. The level of PM reduction is influenced by the content of liquid HC particles in the particulate, which varies with engine design and fuel type. In many cases the HC is reduced from the PM by as much as 90 percent by the catalyst.

Although the oxidation catalyst by itself has not demonstrated great effectiveness at reducing NO<sub>x</sub> emissions, it is very useful with other NO<sub>x</sub>-control methods. Because the combustion characteristics are altered by NO<sub>x</sub>-control methods such as EGR and water-fuel emulsions, the improvement in NO<sub>x</sub> emissions is typically offset by higher PM, CO and HC emissions. Standard NO<sub>x</sub>-control techniques that boost these other emissions will benefit from an oxidation catalyst in the exhaust stream. Together, a NO<sub>x</sub>-control system with an oxidation catalyst can

effectively reduce NO<sub>x</sub>, PM, CO, HC and smoke emissions. One such system, approved under the EPA's urban bus rebuild/retrofit program uses an oxidation catalyst with proprietary engine controls for NO<sub>x</sub> control, yields 40 percent lower NO<sub>x</sub> very low PM emissions to below 0.1 g/bhp-hr. The history of the 20,000 catalysts installed on urban buses in Europe and the U.S. has proven to be virtually maintenance free. In mining and other non-road materials-handling activities, nearly 250,000 units have been installed over the past 30 years, demonstrating significant reductions in CO, HC and PM emissions. Many oxidation catalysts are designed to simply replace an existing muffler in the exhaust system. The cost for truck and bus engines has ranged from \$475 to \$1750, depending on engine size and installation.

## **7.6 Conclusions and Recommendations**

The primary objective of this program element, to obtain precise real time in-situ data comparing the exhaust emissions of competing auto, transit bus, and passenger ferry, remains unfinished. Until Phase II of the program element is completed, the actual emissions produced by competing transit modes, in particular buses and ferries, will remain undefined. As a consequence, attempts to improve regional air quality, to upgrade port facilities and infrastructure, and to increase the speed, efficiency, and cost effectiveness of port operations would likely be delayed by public opposition based on the perception that such objectives would degrade regional air quality.

As discussed in sections 4.0, 5.0 and 6.0, there are a variety of methods for reducing harmful exhaust emissions from marine diesel engines. The best, most sweeping method is the improvement of fuel quality, which has been incrementally accomplished through the reduction of the sulfur content in the fuel. Further sulfur reductions are anticipated in the near future. Public health initiatives today place the higher priorities on the reduction of NO<sub>x</sub> and PM above the other exhaust gases, such as CO, CO<sub>2</sub> and HC. The most cost-effective method of NO<sub>x</sub> reduction is the proven technology of water-fuel emulsions. Depending on the criteria discussed in section 4.3, such as fuel suppliers available and space on board for fresh water and blending equipment, a decision would have to be made on a case-by-case basis whether to purchase pre-blended emulsions from ashore, or whether to install water, fuel and surfactant blending equipment on board the vessel.

In addition to water-fuel emulsions, the technology of exhaust gas recirculation (EGR), is proven effective and minimally intrusive for an engine retrofit. New engines can be purchased with EGR built into the design, and old engines can be modified to employ this technique. Used independently, or together with water-fuel emulsions, NO<sub>x</sub> emissions can be expected to drop dramatically, though not as significantly as the 90 percent reduction demonstrated by the SCR technology. SCR has several drawbacks, however. The catalyst requires much volume in the exhaust system. There is the lifetime capital cost of the urea reagent that is consumed in the catalyzing process. And the retrofit is expensive for its materials and custom fabrication, from vessel to vessel.

Particulate filters, although effective, pose the obstacle of raising the exhaust gas backpressure high enough that engine efficiency and fuel economy is compromised. The oxidizing catalyst, on the other hand, drops into the exhaust system as a relatively inexpensive muffler replacement. The oxidizing catalyst effectively reduces CO, HC and PM emissions, which are precisely what increase with supplementary NO<sub>x</sub>-reduction equipment. The best combination of emissions

reduction equipment, therefore, would employ: either EGR, water-fuel emulsion, or both, to reduce NOx and an oxidizing catalyst to reduce the other harmful emissions of CO, HC and PM.

The operator's financial cost for lowering emissions is undoubtedly greater than if emissions were ignored altogether. Various federal and state environmental agencies, aware of this business consideration, offer financial incentives in tax relief and grants for transportation operators who would make capital improvements to their fleets to improve exhaust emissions and regional air quality.

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## **APPENDIX A**

### **DESCRIPTION OF THE FTIR TEST METHOD**

## APPENDIX A

### FOURIER TRANSFORM INFRARED (FTIR) SPECTROSCOPY ANALYSES

#### I. Introduction

The extractive FTIR measurement method is based on continuous extraction of sample gas from the stack, transporting the sample to the FTIR spectrometer and performing real-time spectral measurement of the sample gas. The sample gas spectra are analyzed in real time for target analytes, archived, and re-analyzed, if necessary, at a later date for other target analytes.

Spectral Insights (SI) has conducted over 75 compliance tests using FTIR on natural gas-fired and diesel engines, using EPA Method 320 or equivalent. Each of these tests was completed successfully. In approximately 50 of the tests, corresponding EPA reference methods for THC, NO<sub>x</sub>, CO<sub>2</sub>, and CO were conducted simultaneously. The agreement between the methods was very good, except in cases where high levels of NO<sub>2</sub> were present. This was found to be due to low converter efficiency in typical chemiluminescent NO<sub>x</sub> analyzers. It was also determined at low NO<sub>x</sub> levels, the chemiluminescent analyzer is subject to fluorescence quenching due to CO<sub>2</sub>. FTIR is not subject to these known problems. We believe that SI possesses the greatest amount of knowledge and experience regarding the use of FTIR spectroscopy on engine (as well as other source) emissions measurements.

The U.S. EPA has accepted all SI-collected FTIR data submitted to it without question, including NO<sub>x</sub> and CO data. For further information on EPA's position on the use of FTIR for NO<sub>x</sub>, CO, and other species, please call either Ms. Rima Dishakjian at (919) 541-0443, Mr. Ken Durkee at (919) 541-5425, or Mr. Mike Toney at (919) 541-5247, all at EPA.

The proposed method will follow all of the procedures described in EPA Test Method 320. SI performed (as Radian Corporation) the successful EPA Method 301 FTIR validation test funded by the Gas Research Institute (GRI) in 1994. The EPA accepted the validation, as stated in an EPA letter to GRI that FTIR can be used at any "gas-fired source". These data are reported in a document published by the Gas Research Institute entitled, *Topical Report: Fourier Transform Infrared (FTIR) Method Validation at a Natural Gas-Fired Internal Combustion Engine*, GRI Document No. GRI-95/0271, December 1995.

SI has successfully used FTIR to determine THC and TNMHC data from engines. Engine exhaust primarily contains methane (CH<sub>4</sub>), ethane, ethylene, and formaldehyde. Because FTIR can measure these species separately, it is straightforward to measure THC and TNMHC using the FTIR system by adding the concentration of the appropriate species, either unweighted, or carbon-weighted. Because the usual detector used in Method 25A analysis is a flame ionization detector (FID), the measurement of THC can be biased with the varying relative responses for each hydrocarbon. However, because the engine exhaust is primarily methane, the differences between THC by FID and FTIR are typically negligible. TNMHC determination has historically been difficult using M25A, due to the high levels of methane expected to be present in the effluent gas and the difficulty of selectively removing methane. A recent EPA-sponsored test of IC engine exhaust measurements at Colorado State University using a "TNMHC" analyzer showed the difficulties with attempts to remove high (1000 ppm) levels of methane.



## II. Summary of FTIR Method

FTIR measurement is based on the absorbance of infrared energy by gas phase compounds. Most molecules absorb infrared energy at characteristic frequencies based on the molecular vibrational and/or rotational motion within the molecule. The absorption characteristics of a particular compound can be used to identify and quantitate the concentration of that compound. The concentration of a single target compound is related to its absorbance according to Beer's Law:

$$A(\nu) = a(\nu)bc$$

Where:

- $A(\nu)$  = absorbance at wavelength  $\nu$ ,
- $a(\nu)$  = absorption coefficient at wavelength  $\nu$ ,
- $b$  = path length, and
- $c$  = concentration.

If more than one compound absorbs light at a given wavelength, then the total absorbance is found from a linear combination of Beer's Law for each compound:

$$A_{\text{total}}(\nu) = b \sum_{i=1}^N a_i(\nu)c_i$$

Where:

- $A_{\text{total}}$  = total absorbance at wavelength  $\nu_i$ ,
- $a_i(\nu)$  = absorption coefficient for compound I at wavelength  $\nu$ ,
- $c_i$  = concentration of compound I,
- $N$  = total number of absorbing compounds, and
- $b$  = path length.

Compounds with very sharp spectral features, such as CO, can exhibit nonlinear analyzer response, requiring correction algorithms to accurately calculate concentrations. Correction algorithms are generated by measuring the spectrum of the compound at several different concentrations and fitting the resulting data to an appropriate correction curve.

Quantitation of each target compound is based on the application of a reference spectrum that is specific to that compound and is measured at a known concentration, temperature, and pressure. For the target compounds, quantitation is performed by selecting characteristic absorbance regions that have minimal interferences from other compounds present in the gas stream.

The classical least squares (CLS) method is applied to fit the reference spectra to the sample spectrum, with the resulting scaling factors used to calculate concentrations. The CLS method finds the set of concentrations that minimizes the residuals in the analysis region and provides a confidence interval for each concentration calculated. The confidence interval is used as a

diagnostic to determine how well the CLS method fit was accomplished. It is used to assess instrument performance and to alert the user to review the data for the presence of new or elevated concentrations of interferants in the sample.

## **APPENDIX B**

### **EPA TEST METHOD 1 — SAMPLE AND VELOCITY TRAVERSES FOR STATIONARY SOURCES.**

## **APPENDIX C**

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## **APPENDIX D**

### **EPA TEST METHOD 3A — DETERMINATION OF OXYGEN AND CARBON DIOXIDE FROM STATIONARY SOURCES (INSTRUMENT ANALYZER PROCEDURE).**

## **APPENDIX E**

**EXHAUST EMISSIONS MEASUREMENT, RECOMMENDATIONS FOR  
RECIPROCATING ENGINES AND GAS TURBINES. APPENDIX  
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## **APPENDIX F**

### **EPA TEST METHOD 320 — MEASUREMENT OF VAPOR PHASE ORGANIC AND INORGANIC EMISSIONS BY EXTRACTIVE FOURIER TRANSFORM INFRARED (FTIR) SPECTROSCOPY SOURCES.**

## **APPENDIX G**

**AVL MODEL SPC 472 SMART SAMPLER — BROCHURE.**



## **APPENDIX H**

**AVL MODEL SPC 472 SMART SAMPLER — CUT SHEET FROM WEB SITE.**

## **APPENDIX I**

**MAGAZINE ARTICLE FROM MECHANICAL ENGINEERING, "A FLEXIBLE  
SAMPLER FOR DIESEL EXHAUST," FEATURING SIERRA INSTRUMENTS.**

## **APPENDIX J**

**SIERRA INSTRUMENTS, MODEL BG MICRO-DILUTION TEST STAND  
— BROCHURE.**

## **APPENDIX K**

### **SIERRA INSTRUMENTS, MODEL BG-1 MICRO-DILUTION TEST STAND — OPERATING INSTRUCTIONS.**

## **APPENDIX L**

**MODEL BG-1 CERTIFICATE OF CONFORMITY FROM TUV HANNOVER.**

## **APPENDIX M**

### **MODEL 780S THERMAL MASS FLOW METER — PRODUCT BULLETIN.**

## **APPENDIX N**

**KRAL VOLUNTEER FUEL METERING SYSTEM — CUT SHEET FROM WEB  
SITE.**

## **APPENDIX O**

### **WIRELESS DATA CORPORATION, MODEL 1625 TORQUE SENSOR ASSEMBLY — PRODUCT BULLETIN.**





## **APPENDIX P**

**DDEC IV SYSTEM PRODUCT DATA — CUT SHEET FROM WEB SITE.**

## **APPENDIX Q**

### **DDEC REPORTS — USER MANUAL**